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Septic tank nutrients in groundwater entering Lake Sallie, Minnesota

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SEPTIC TANK NUTRIENTS IN GROUNDWATER
ENTERING LAKE SALLIE, MINNESOTA

By
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This thesis submitted by David Robert Lee in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota is hereby approved by the Faculty Advisory Committee under whom the work has been done.

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Dean of the Graduate School

Permission

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Department Biology

Degree Master of Science

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Date 29 August 1972

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shore. The nitrate-rich seepage represented only 30% of the total inflow along the shore, indicating a nitrate cap on the water table.

ABSTRACT

The nutrient contribution of septic tanks to a lake was evaluated at Lake Sallie, in glacial outwash terrain of northwestern Minnesota. Groundwater entering the lake was collected by covering 0.258 m^2 of lake bed with a bottomless cylinder vented to a deflated plastic bag. Inflow velocity ranged from 0.01 to 2.5 micrometers per second along 30% of the lakeshore. Groundwater inflow along an 800 m segment of shore amounted to 4.50×10^5 m^3/year, and was uniformly distributed along the shore, but decreased exponentially away from shore.

Effluent from a heavily-used lakeside septic tank fanned out along the surface of the water table, and entered the lake within 9 m of shore. Phosphorus was fixed in the soil near the septic tank but 40% of the effluent nitrogen reached the lake. Sampling lakeward and landward of five septic tanks indicated that nitrate and possibly ammonium ions travel in groundwater and that nitrogen is contributed to groundwater by septic tanks.

Seepage entering the lake contained as much as 3.67 mg soluble orthophosphate/liter but no pattern was apparent regarding land use and phosphorus content of groundwater. A nearby eutrophic lake was a suspected source of both phosphorus and nitrogen in groundwater inflow. Along the only lakeshore adjacent to cropland, seepage was nitrate-rich (2.19 to 50.4 mg nitrate nitrogen/liter) within 8 m of shore and nitrate-poor (less than 0.022 mg nitrate nitrogen/liter) farther off-

INTRODUCTION

Many cottages and summer homes along lakes and streams have septic tank or cesspool waste disposal systems which discharge into the soil. Several writers (Nichols, 1965; Hasler and Ingersoll, 1968; Bennett, 1969; and Rose, 1972) have suggested that nutrients from such sources pose an enrichment hazard to surface waters.

Schraufnagel and others (1967) estimated that 42% of the nitrogen and 2.3% of the phosphorus reaching surface waters in Wisconsin came from groundwater. Tilstra and others (1971) found that septic tank wastes were being safely disposed in lava terrain at Waldo Lake, Oregon; but they warned that continued use of the system might endanger the lake. Brydges (1972) presented iron/phosphorus ratios of lake water as evidence of septic tank enrichment in Ontario. Iron/phosphorus ratios ranged from 71 to 18 for six lakes without cottages, from 9 to 3.5 for three lakes with cottages, and from 10 to 0.33 for three lakes with both municipal and agricultural nutrient sources.

Evidence that subsurface waste disposal is responsible for lake enrichment appears entirely inferential. There are no detailed studies of the long term changes which follow lakeshore development, and records of groundwater nutrient concentrations prior to development are nearly always lacking.

This study was undertaken to develop a method for collection of groundwater entering lakes, and to use this method, along with well sampling, to find the amount and sources of nutrients in groundwater flowing into Lake Sallie.

DESCRIPTION OF STUDY AREA

Lake Sallie is in northwestern Minnesota 3.5 km southwest of Detroit Lakes, in a hilly area with many closed depressions (Figure 1). The soils are dark, excessively drained, sandy loams developed from calcareous gravelly outwash (Becker Soil and Water Conservation District 1968). The clay in the soils is assumed to be predominately montmoillonite (Diedrick, 1972). Clean, surficial sand and gravel described as glacial outwash is 5 to 30 m thick and overlies a clay-silt layer (McBride, 1972a).

Cabins occur on the southeastern, western and northern margins of the lake (Figure 1). Land adjacent to the southwestern shoreline is largely agricultural and deciduous forest borders the northern half of the lake.

Most of the 186 lakeside dwellings have septic tanks, but many cottages are not used intensively. Less than half are used more than three weeks each summer and only eight or ten may be considered permanent or semi-permanent. Based on observations during the two-year study and on interviews with many lakeside inhabitants, occupancy was estimated at 20,000 to 35,000 man-days per year.

McBride (1972a) reported a net groundwater inflow into Lake Sallie of 2657 and 3059 acre-ft (1 acre-ft = 1,240 m^3) for water years 1969 and 1970, respectively, when calculated as a residual. By use of the Darcy equation he calculated inflows of 1510 and 1420 acre-ft/year on the basis of seasonal maximum and minimum water table conditions.

Fig. 1.--Map of Lake Sallie area. Reproduced from United States Geological Survey Audubon, Minnesota quadrangle. Contour interval is 10 feet. Lake levels are in feet above sea level.

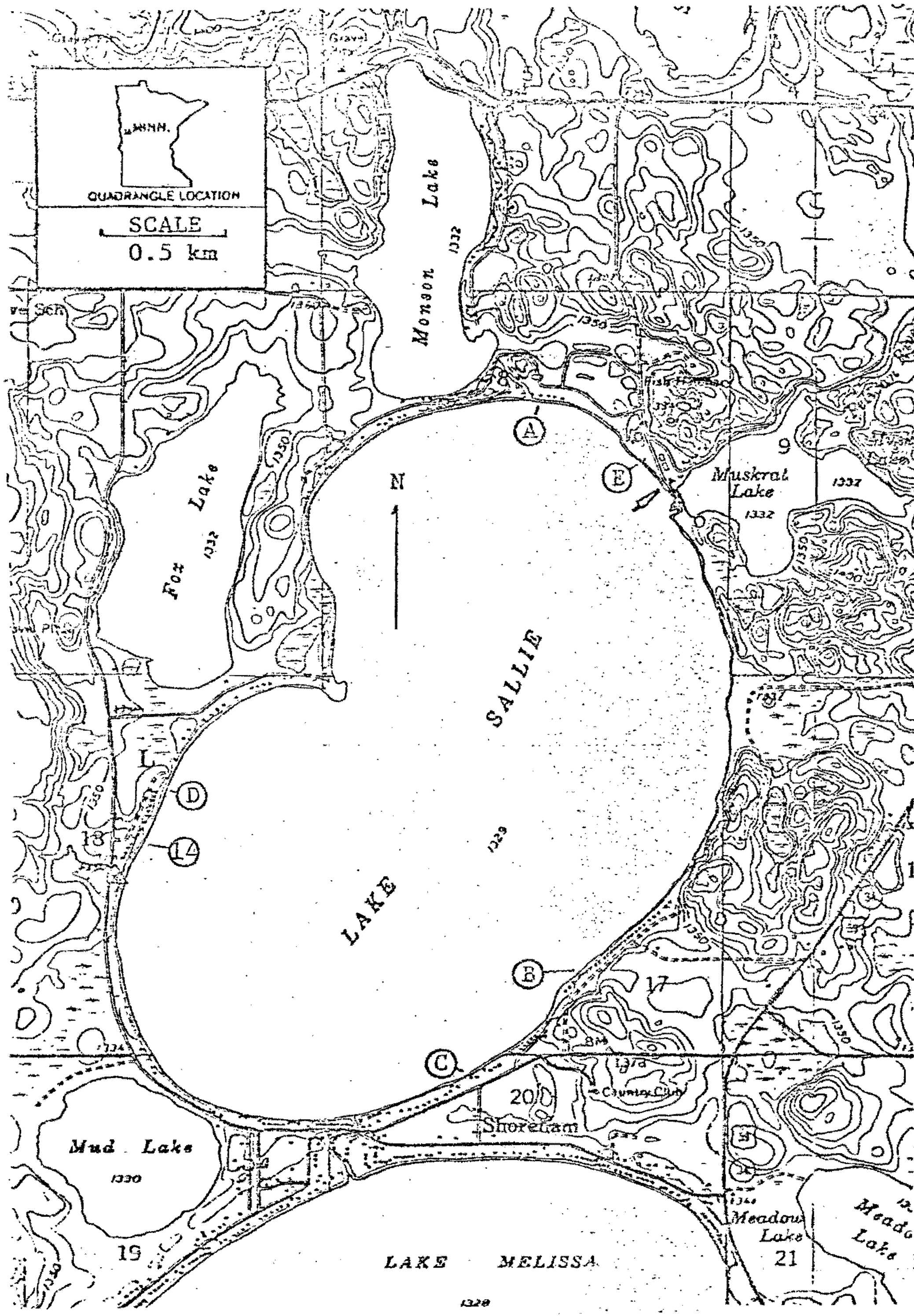
Legend:

■ = house(s)

Δ = U. S. Geological Survey well log referred to in text.

= State Fish Hatchery

B = Septic tank study sites


QUADRANGLE LOCATION
MINN.
SCALE
0.5 km
Monson Lake
1332
Fox Lake
1332
N
LAKE SALLIE
1329
Muskrat Lake
1332
A
B
C
D
E
14
9
17
18
20
19
21
Mud Lake
1330
Shoreham
Country Club
Meadow Lake
LAKE MELISSA
1328
1350

Shallow areas of Lake Sallie have mainly sand and gravel bottoms, but in dense weed beds, in water more than 1.5 m deep, 4 cm of light-colored, finely-divided material has accumulated.

Precipitation in 1971 exceeded the normal by 16.97 cm. The first half of 1971 received less than normal rainfall, but the second half was unusually wet (Table 1).

TABLE 1

MONTHLY PRECIPITATION AT DETROIT LAKES, MINNESOTA

Month	Precipitation (cm)		
	Normal (1931-60)[a]	1971[b]	Departure From Norm
January	1.73	1.88	+ 0.15
February	1.65	2.34	+ 0.69
March	2.31	1.83	- 0.48
April	5.31	2.13	- 3.18
May	7.45	4.64	- 2.81
June	10.03	13.44	+ 3.41
July	8.82	11.48	+ 2.66
August	10.03	6.96	- 3.07
September	4.88	17.08[c]	+12.20
October	3.30	11.38	+ 8.08
November	2.59	3.05	+ 0.46
December	1.78	0.64	- 1.14
Annual Total	59.87	76.84	+16.97

[a]U.S. Department of Commerce (1964)

[b]U.S. Department of Commerce (1971)

[c]Spilman (1972)

MATERIALS AND METHODS

The study involved sampling and analysis of 1) groundwater in the vicinity of lakeside septic tanks and 2) seepage inflow near the margin of the lake.

Septic Tank Bracketing

At each of four sites, two standard wells (Figure 2) were driven about 1 m into the water table lakeward and landward of the septic tank on a line perpendicular to the lakeshore. At a fifth site it was possible to locate a well only on the lakeward side. Elevations of well heads were referenced to lake level which was read on a staff gauge at the Muskrat Lake inlet (Figure 1).

Groundwater chemistry was monitored monthly from July, 1970, to December, 1971. In 1971 water table elevations were measured prior to sampling. A sample was collected after pumping 40 to 60 liters of water from each well with a pitcher pump. Groundwater temperature was measured with a thermistor thermometer after sampling.

Seepage Measurement and Collection

Seepage into the lake was collected by covering a 0.258 m^2 area of lake bed with a bottomless cylinder vented to a deflated plastic bag (Figure 3). The cylinder was pushed slowly, open end down, into the lake bed until its closed end was about 4 cm above the sediment. It was positioned to elevate the vent hole slightly so that gas, originating in the sediment, could freely escape. The cylinder was left for

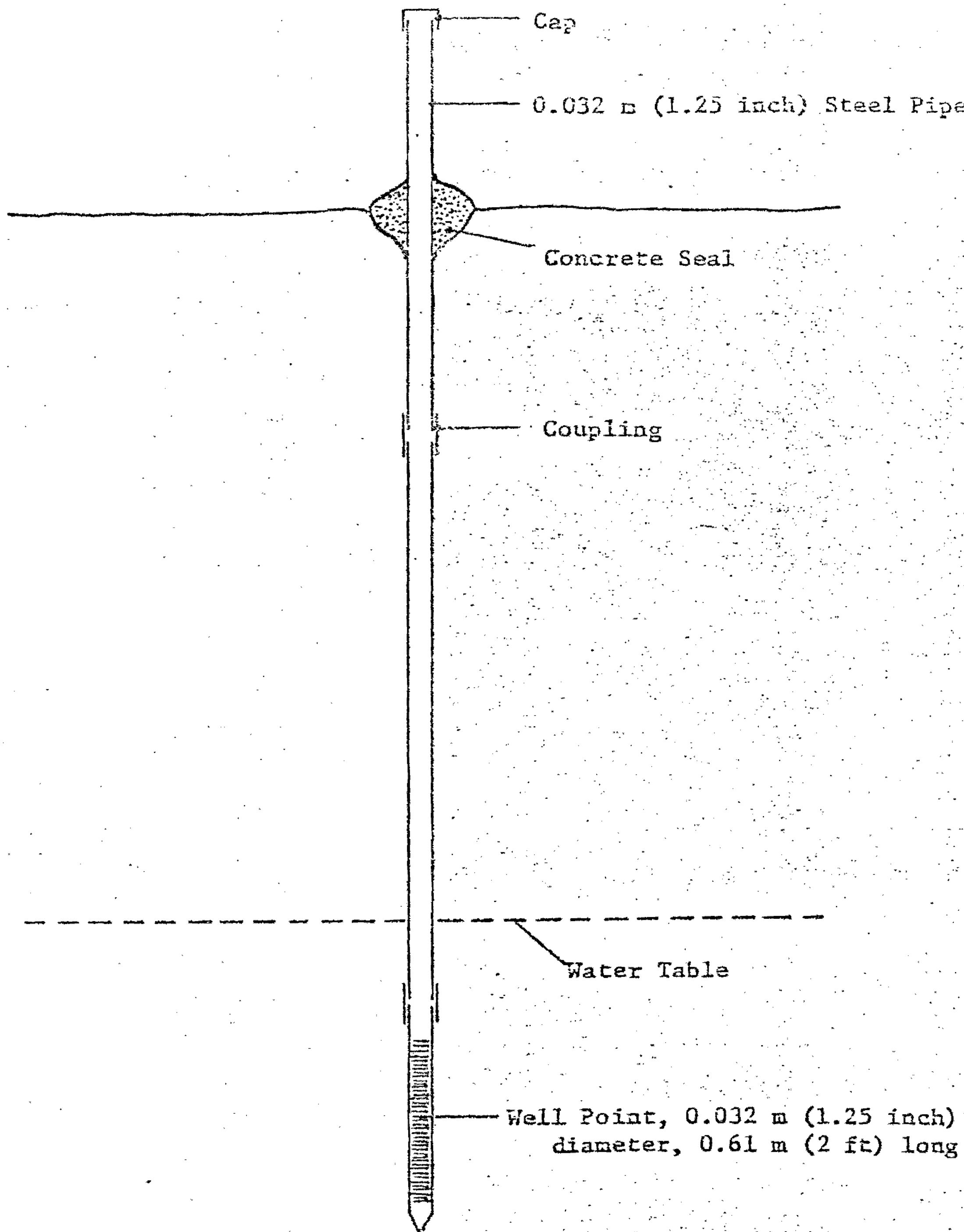


Fig. 2.--Standard observation well.

Legend:

1. 4 liter, 0.017 mm thick plastic bag (open end was heat sealed)
2. Rubber band wrap
3. 0.64 cm (0.25 inch) inside diameter, polythylene tubing
4. 0.79 cm (0.31 inch) inside diameter, soft-rubber tubing
5. Number 5½, one-hole, rubber stopper with polyethylene tubing
6. Epoxy-coated cylinder, 0.15 cm x 57 cm diameter (end-section of a 55 gallon steel drum)

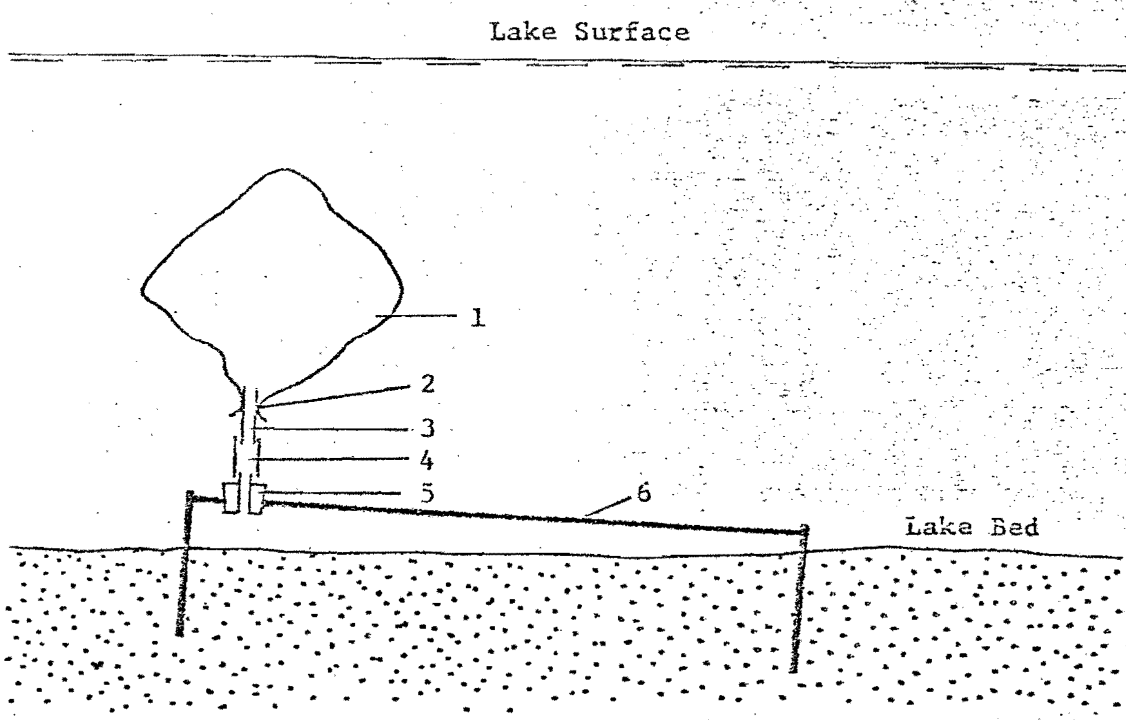


Fig. 3.—Full-section view of seepage collector.

several days to enable benthic organisms to escape. Then a stopper with tube was inserted into the cylinder hole. To collect a sample, a deflated plastic bag was connected to the tube, and left until it contained a ½ to 3 liter sample, or for a specified time. Less than 5 ml of lake water entered the bag during connection. The sample volume was measured and a portion retained for chemical analysis. Collectors were left in position with tubes open to the lake between sampling dates. They were removed with a light-weight, steel picket notched to hook the lower cylinder edge.

Seepage velocity was calculated using the following equation:

$$\frac{\text{liters of water in the bag}}{\text{hours of elapsed time}} \times 1.075 = \text{velocity as micrometers per second } (\mu m/s).$$

The factor 1.075 simply converts liters per hour and area of the cylinder to micrometers per second. Expressed in this way, velocity is numerically equivalent to discharge as milliliters per second over a square meter of lake bed.

Initially, 0.32 cm (1/8 inch) inside diameter tubing and 0.40 liter plastic bags (0.070 mm membrane) were used. A test showed that this tubing reduced velocity by 30% where larger tubing (1.4 cm and 0.64 cm) gave seepage velocities of 0.7 μm/s. After 22 June 1971, 0.64 cm inside diameter tubing and 4-liter plastic bags (0.017 mm membrane) were used.

During ice cover, a one-hole screw plug with a longer tube enabled connection of the plastic bag through the ice. The tube was removed with an underwater wrench (Figure 4) after each sampling to prevent its freezing and stopping flow.

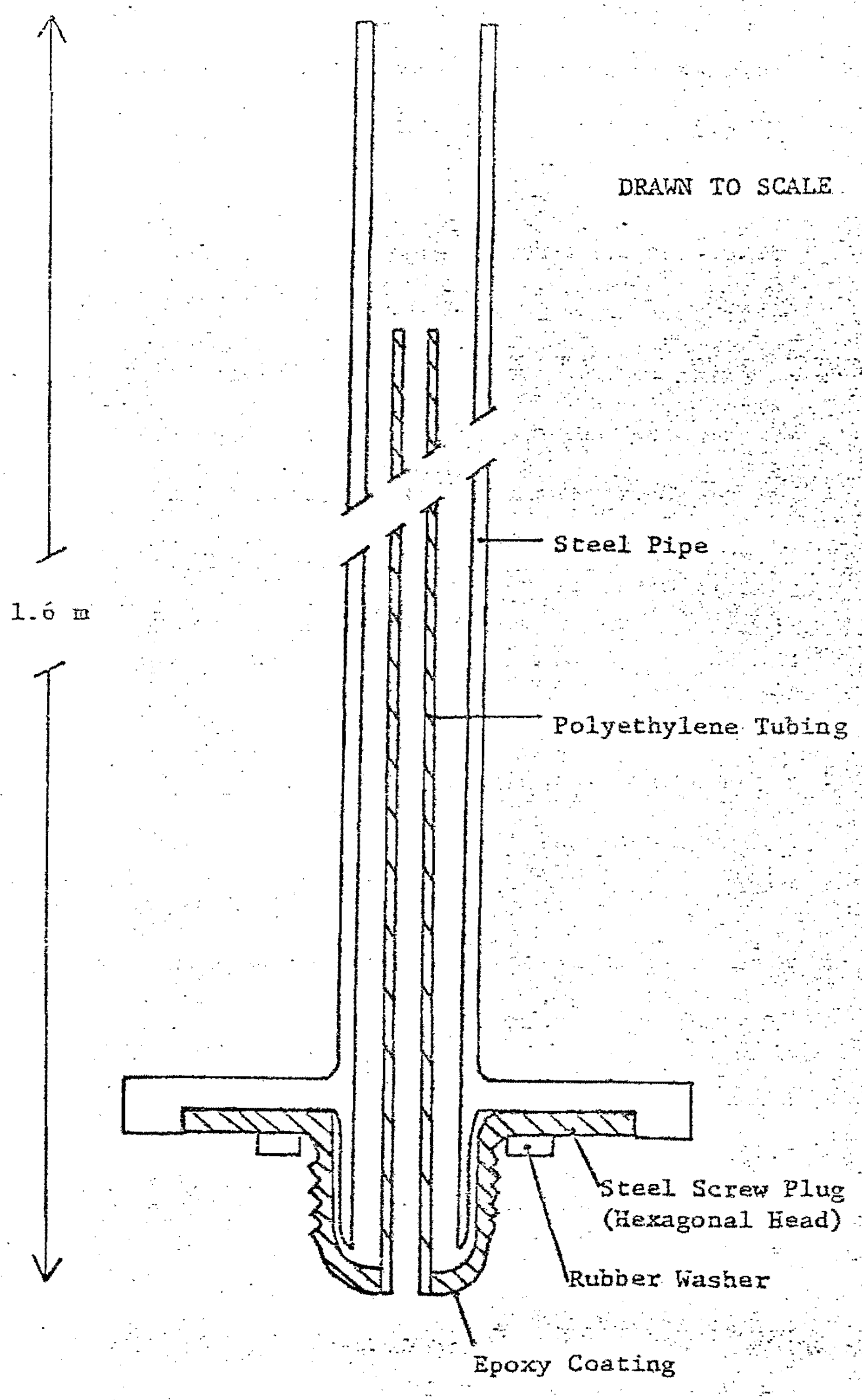


Fig. 4.--Full-section view of underwater wrench and one-hole screw plug with tube. Full-section view. When bent slightly and inserted into the wrench handle, the tube holds the plug in place until attached and also guides the wrench to the plug for removal.

Measurement points were mapped using landmarks, aerial photographs, and a graduated rope. Water depth was measured with a pole marked at 0.1-m intervals. A metal detector was used to find collectors beneath ice cover when marker stakes were obliterated. Except during ice cover, work was done by wading and shallow diving. Measurements were made in water 0.15 to 1.6 m deep with no regard for bottom type.

Tracer Study

Wells

Twelve, small diameter wells (Figure 5) and 15 seepage collectors were used to assess contributions from a single septic tank. Small diameter wells were preferred because they could be moved easily. They were placed in two rows parallel to the shoreline on the lakeward side of the septic tank. Perforations in these wells allowed some soil to enter from the saturated zone.

Tracer

Forty-five kg (100 lb) of crushed rock salt (NaCl) were dissolved in 350 liters of water and stirred into the settling tank. This was done twice because 5 days after the first dose, the influent line clogged and the owner, believing the septic tank was plugged, had it cleaned. This may have provided a pre-tracer because little or no discharge would occur while the septic tank refilled. A second slug of salt was added on 28 August 1971 when the septic tank had refilled.

Sample Collection

Wells were sampled with a polyethylene sampler (Figure 5) similar to sand pumps used by local well drillers. The sampler was

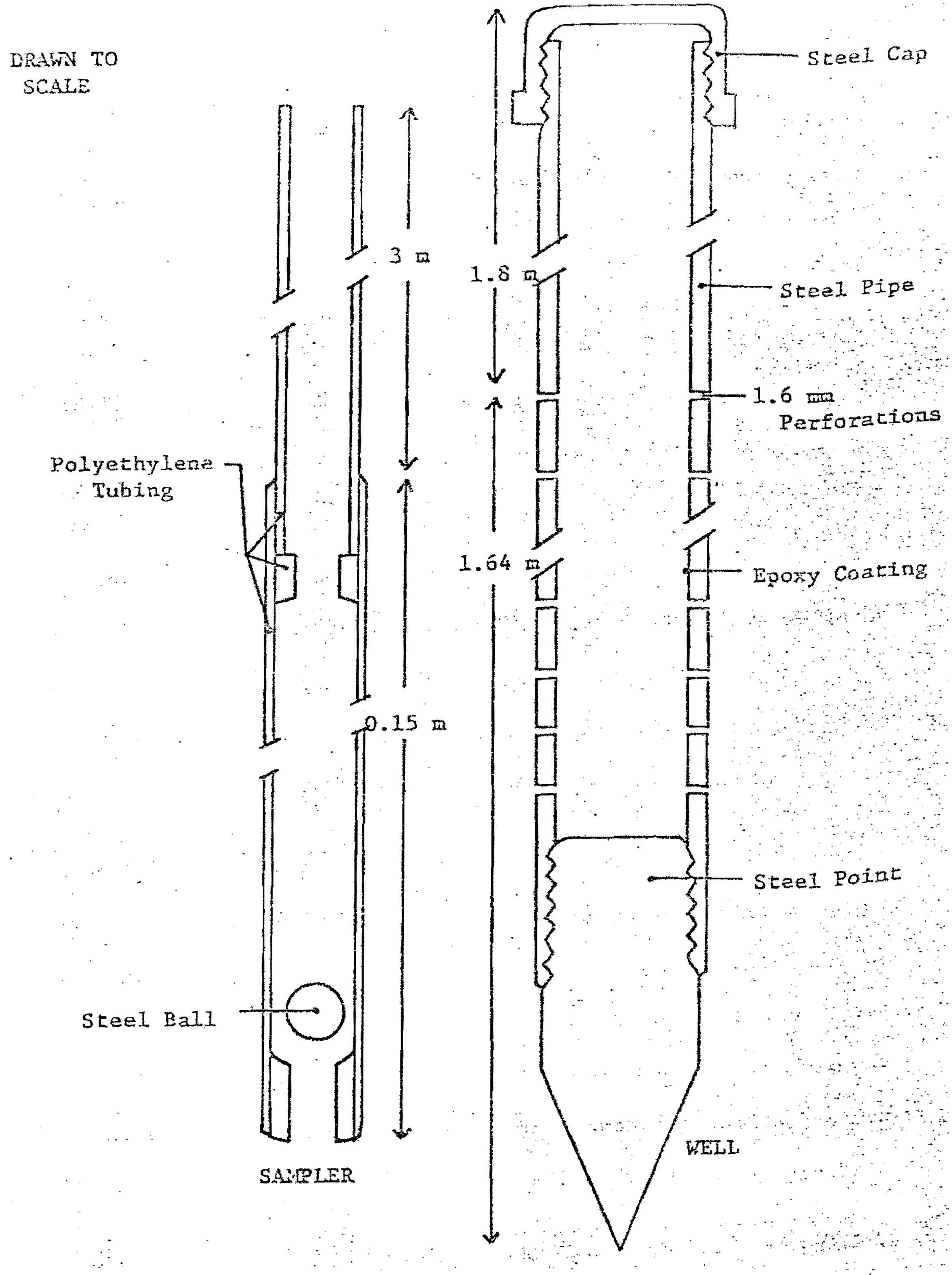


Fig. 5.—Full-section view of small-diameter well and polyethylene sampler.

inserted to the bottom of a well and jerked up and down; the ball in the tip acted as a check valve on the upstroke but permitted inflow on the downstroke. When full, the sampler was removed from the well and emptied. The first sampler load was discarded. To minimize disturbance of groundwater flow, only 0.6 liters of water and 20 to 30 g of soil were removed at each sampling. Wells and seepage collectors were sampled semimonthly from August through November 1971.

Chemical Analysis

Water samples were either frozen and analyzed several weeks later or stored at 0 to 5 C and analyzed within 48 hr after collection. Analyses for ammonia, nitrite, and nitrate nitrogen, and for soluble orthophosphate were according to the 12th and 13th editions of *Standard Methods* (American Public Health Association, 1965, 1971). Preliminary digestion for total phosphate followed the persulfate procedure of the Environmental Protection Agency (Dominick, 1971). To obtain particulate matter (if present) for total phosphate determination, the sample was shaken, allowed to settle 30 to 40 s and a portion pipetted from the center of the sample bottle. Specific conductivity was measured at 20 C with a conductivity bridge. Chloride was determined with a specific-ion electrode assembly. Filtration through medium grade filter paper (equivalent to Sargent 501) preceded all determinations except ammonia and total phosphate.

Geological Data

At all well sites limited information on surficial geology was obtained by hand augering, by the appearance of the groundwater, and by the feel of the driver during well installation. The United States Geological Survey conducted a concurrent study and provided additional information.

RESULTS

Septic Tank Bracketing

Location and features of the five septic tank study sites are shown in Figure 1 and Table 2. Measurement of water table and lake elevation in 1971 indicated that groundwater movement was lakeward at all sites except C and E in late winter and at Site A in spring when flow was away from the lake.

Groundwater temperature was highest (10.2 to 13.9 C) in September and October and lowest (below 0 to 4.5 C) in March. But at Site D, where there was more overburden, groundwater did not reach minimum temperature (2.1 and 2.9 C) until 23 May 1971.

A belated test indicated that soluble orthophosphate results could be lowered by freezing samples for storage (Table 3). Lake water was least affected but had 10% less orthophosphate after freezing Total phosphate, inorganic nitrogen forms and specific conductivity we only slightly affected by freezing. Samples that were frozen for storage are marked with an asterisk.

Groundwater at the five study sites was pervaded with nutrien which made it difficult to attribute contamination to any source. At Sites B and C, orthophosphate was often present in higher concentrati landward of the septic tank, but at Site E was generally lower on th landward side (Table 3). At Site B total phosphate was greater land ward of the septic tank, but at Sites C and E was generally lower on

TABLE 2

FEATURES OF SEPTIC TANK STUDY SITES, A THROUGH E

Site	Site Dimensions (m)[b]				Material Around Septic Tank	Age of Dwelling (yr)	Septic Tank Use
	A	B	C	D			
A	4	10	a	1	medium to coarse sand	35	5 people; summer weekends 1967-71
B	9	9	17	0	sand	35	3 people; summers
C	16	12	15	0	fine sand	35	2 to 5 people; summer 1960-69, summer week-ends 1970-71
D	17	13	27	3½	fine to coarse sand	4	6 people; summer 1968-70, 2 people summer seek-ends 1971
E	20	26	38	½	sand; small amount of clay at lakeward well	55	5 people year-round, 1951-71

[a]No well installed due to clay at water table.

[b]Legend:

Landward Well ← C → Septic Tank ← B → Lakeward Well ← A → Lake

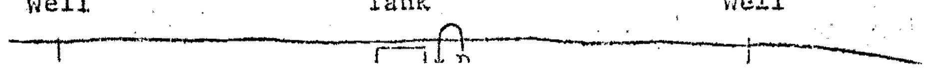


TABLE 3

ANALYSES OF FRESH AND FROZEN WATER SAMPLES

Source	mg PO_4/liter		mg N/liter			Specific Conductance (μmho/cm. at 20 C)
	Soluble Orthophosphate	Total Phosphate	Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen	
Lakeward well at Site A	0.65 (0.20)[a]	2.88 (2.32)	0.46 (0.47)	0.000 (0.000)	0.003 (0.006)	808 (802)
Lakeward well at Site D	0.34 (0.06)	0.20 (0.24)	0.00 (0.00)	0.001 (0.001)	8.20 (8.20)	476 (470)
Landward well at Site D	0.43 (0.07)	0.48 (0.44)	0.25 (0.30)	0.000 (0.000)	0.002 (0.004)	446 (440)
Muskrat Lake	1.38 (1.26)	1.32 (1.28)	1.20 (1.28)	0.010 (0.009)	0.132 (0.130)	522 (510)

[a]Parentheses indicate results on frozen samples

the landward side (Table 4). At Site D, both wells were about the same with respect to orthophosphate and total phosphate concentration (Tables 3 and 4).

Nitrogen was invariably more concentrated lakeward of all four septic tanks (Tables 5 and 6). Ammonia was the dominant form at Sites B, C, and E and nitrate at D.

Nitrate movement was apparent at Sites B and D. At B, the landward well had a maximum of 0.34 mg/liter in September 1970 and the lakeward well had a maximum of 0.24 mg/liter in June of 1971 (Table 6), suggesting that the nitrate source was upstream from both wells. At Site D, the lakeward well peaked at 20.0 and 13.3 mg/liter in September of both 1970 and 1971, three months after summer occupancy began (Table 7). The landward well at D did not exhibit significant variation and, with one exception, was always much lower in nitrate than the lakeward well. This suggests that the septic tank was the nitrate source. These observations indicated groundwater velocities of 1.1 to 2.0 μm/s (0.31 to 0.57 ft/day) at Sites B and D, respectively. Nitrate declined sharply in the landward well at Site D when the well was driven 0.5 m deeper (Table 7) suggesting that nitrate was concentrated near the surface of the saturated zone.

Results from a single lakeward well at Site A showed consistency with respect to nitrogen forms (Table 8).

Analyses indicated that nitrate and possibly ammonia travel in groundwater and that at Sites D and E septic tanks appeared to contribute nitrogen to groundwater.

TABLE 4

ORTHOPHOSPHATE CONCENTRATION (mg/liter) AT SINGLE WELLS LAKEWARD AND LANDWARD OF FOUR SEPTIC TANKS[a]

	Site B		Site C		Site D		Site E	
Date	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward
1970								
7 July	0.63	2.08[b]	0.50	0.00	--	--	--	--
28 July	0.57	3.60[b]	1.03	0.56	1.65	--	--	--
3 August	2.75	4.42[b]	0.64	0.38	0.90	--	--	--
10 August	0.83	1.55	0.60	0.57	0.63	2.40	4.70	1.28
30 August	0.58	1.35	0.47	0.35	0.47	0.30	0.50	0.32
13 September	0.49	1.03	0.47	0.58	0.25	0.00	0.20	0.24
1971								
5 June	0.77	1.63	0.57	0.72	0.84	0.77	0.16	1.11
26 June	0.01	1.41	1.13	0.27	0.56	0.23	0.73	0.32
22 July	0.29	1.07	0.51	0.39	0.31	0.23	0.31	--

[a]Omits data on frozen samples

[b]The well was within a meter of a pit latrine and was moved 5 m further from the lake after these samples were taken.

TABLE 5

TOTAL PHOSPHATE CONCENTRATION (mg/liter) AT SINGLE WELLS LAKEWARD AND LANDWARD OF FOUR SEPTIC TANKS

	Site B		Site C		Site D		Site E	
Date	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward
1971								
16 April*	--	1.66	0.24	0.34	0.42	0.31	1.04	--
8 May*	--	1.50	0.07	0.05	1.12	0.90	3.90	2.35
26 June*	0.81	2.86	--	0.56	1.05	0.92	2.36	0.72
22 July	0.89	1.71	0.80	0.63	1.07	0.71	2.12	0.91
10 September*	0.50	1.90	0.40	0.36	0.20	0.60	2.14	--
10 October*	0.66	1.76	0.42	0.42	0.26	0.42	3.24	--
3 December*	0.68	2.08	0.66	0.56	0.38	0.56	2.38	1.24

*Samples which were frozen for storage

-- Indicates no data

TABLE 6

AMMONIA NITROGEN CONCENTRATION (mg/liter) AT SINGLE WELLS LAKEWARD AND LANDWARD OF FOUR SEPTIC TANKS

Date	Site B		Site C		Site D		Site E	
	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward
1970								
7 July	0.14	0.43	0.81	0.11	--	--	--	--
28 July	0.11	0.04	0.96	0.15	0.21	--	--	--
3 August	0.17	0.36[b]	0.87	0.52	0.10	--	--	--
10 August	0.23	0.25	0.94	0.68	0.15	0.16	4.07	0.10
30 August	0.28	0.14	1.00	0.61	0.22	0.18	3.92	0.13
13 September	0.31	0.31	1.10	0.68	0.29	0.32	4.0	0.22
3 October*	0.36	0.33	0.99	0.56	0.20	0.22	4.73	0.07
23 October*	0.15	0.18	0.90	0.60	0.08	0.03	3.8	0.03
13 November*	0.16	0.21	0.82	0.63	0.15	a	4.1	0.12
29 December*	Frozen	0.10	0.82	0.68	0.16	0.17	3.4	Frozen
1971								
23 January*	Frozen	0.08	0.92	0.68	0.08	0.01	3.4	--
6 March*	Frozen	0.18	0.71	Frozen	0.06	0.22	3.7	Frozen
3 April*	Frozen	0.18	0.89	0.73	0.13	0.32	4.0	Frozen
16 April*	Frozen	0.15	0.51	0.21	0.04	0.01	3.9	Frozen
8 May*	Frozen	0.00	0.32	0.10	0.00	0.01	2.7	0.00
23 May*	0.25	0.00	0.43	0.29	0.20	0.42	0.50	--
5 June	0.77	0.16	0.65	0.15	0.19	0.77	3.9	0.08
26 June	0.01	0.04	0.45	0.19	0.00	0.23	3.8	0.00
22 July	0.29	0.08	0.53	0.24	0.00	0.23	3.8	0.00
9 September*	0.18	0.11	1.10	0.70	0.00	0.06	3.9	--
10 October*	0.06	0.19	0.95	0.78	0.00	0.21	4.74	--
3 December*	0.12	0.11	0.78	0.65	0.00	0.07	2.54	0.00

*Samples frozen for storage

--Indicates no data

[a]Well was driven 0.531 m deeper

[b]Well was moved about 5 m further from the lake

TABLE 7

NITRATE NITROGEN CONCENTRATION (mg/liter) AT SINGLE WELLS LAKEWARD AND LANDWARD OF FOUR SEPTIC TANKS

Date	Site B		Site C		Site D		Site E	
	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward	Lakeward	Landward
1970								
21 July	0.048	0.010	0.005	0.006	--	--	--	--
28 July	0.060	0.013	0.006	0.007	1.57	--	--	--
3 August	0.043	0.006[b]	0.007	0.006	4.55	--	--	--
10 August	0.004	0.107	0.005	0.004	0.258	1.50	0.004	0.214
30 August	0.006	0.32	0.007	0.013	1.56	0.56	0.013	0.26
13 September*	0.008	0.34	0.098	0.010	17.5	0.410	0.183	0.79
3 October*	0.008	0.041	0.004	0.062	20.0	0.480	0.005	0.142
23 October*	0.009	0.004	0.001	0.005	14.7	0.348	0.007	0.015
13 November*	--	--	--	--	--	a	--	--
29 December*	Frozen	0.005	0.004	0.005	13.1	0.004	0.006	Frozen
1971								
23 January*	Frozen	0.005	0.007	0.007	9.90	0.008	0.009	--
6 March*	Frozen	0.008	0.004	Frozen	4.02	0.012	0.006	Frozen
3 April*	Frozen	0.011	0.007	0.222	2.55	0.006	0.006	Frozen
16 April*	Frozen	0.002	0.004	0.480	3.74	0.004	0.004	Frozen
8 May*	Frozen	0.002	0.002	0.228	3.70	0.001	0.004	0.000
23 May*	0.040	0.003	0.003	0.061	3.88	0.003	0.003	--
5 June	0.075	0.005	0.008	0.000	2.78	0.003	0.006	0.300
26 June	0.240	0.005	0.007	0.005	1.25	0.009	0.010	1.34
22 July	0.024	0.007	0.008	0.003	3.55	0.004	0.002	0.549
10 September*	0.003	0.002	0.006	0.002	8.96	0.004	0.002	--
10 October*	0.005	0.001	0.002	0.001	13.3	0.002	0.002	--
3 December*	0.009	0.002	0.002	0.002	10.5	0.002	0.002	0.50

[a]Well was driven 0.513 m deeper.

-- Indicates no data.

*Samples frozen for storage

[b]Well was moved about 5 m further from the lake.

TABLE 8

PHOSPHORUS AND NITROGEN CONCENTRATION (mg/liter) AT A WELL LAKEWARD OF THE SEPTIC TANK AT SITE A

Date	Soluble Orthophosphate	Total Phosphate	Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
1970					
21 July	1.63	--	0.62	0.000	0.006
28 July	1.50	--	0.55	0.000	0.028
3 August	2.34	--	0.57	0.000	0.007
10 August	2.05	--	0.58	0.000	0.172
30 August	1.50	--	0.54	0.001	0.007
13 September	1.20	--	0.64	0.001	0.009
3 October*	--	--	0.52	0.002	0.004
23 October*	--	--	0.50	0.001	0.005
13 November*	--	--	0.62	0.005	--
29 December*	--	--	0.50	0.000	0.001
1971					
23 January*	--	--	0.55	0.004	0.007
6 March*	--	--	1.8	0.005	0.001
3 April*	--	--	0.50	0.000	0.009
16 April*	--	1.68	1.5	0.001	0.004
8 May*	--	2.25	0.38	0.000	0.003
23 May*	--	--	0.52	0.000	0.003
5 June	3.00	1.31	0.46	0.000	0.005
26 June	2.72	2.78	0.38	0.000	0.006
22 July	1.28	2.58	0.53	0.002	0.006
9 September*	--	1.96	0.75	0.001	0.002
10 October*	--	2.18	0.49	0.000	0.002
3 December*	--	2.60	0.53	0.000	0.002

*Samples which were frozen for storage.

Performance of Seepage Collector

Tests

The seepage collector was first tested near the fish hatchery where a dam holds the level of Muskrat Lake about 1.5 m higher than Lake Sallie (Figure 1). Successive samples from a single collector were chemically consistent and distinct from lake water (Appendix, Collector 1A). Two collectors set at the fish hatchery, 0.15 m apart, 7 m off-shore, in 0.55 m of water, and monitored over a two-month period, gave velocities from 0.596 to 0.854 μm/s (Figure 6). The collectors differed by about 0.1 μm/s. Variations were strikingly synchronous but did not always appear to be due to changes in relative elevation of the two lakes (Figure 6).

The effect of changes in the relative elevation of the two lakes may have been obscured by 1) changes in atmospheric pressure and temperature (Christiansen, 1944; Peck, 1960) and 2) lack of simultaneous measurement of velocity and lake levels. Compared with daily averages, individual measurements varied by about 10% (Appendix, Collectors 1E and 1F).

Collector 1E, in place for 12 days, presumably indicated groundwater concentrations and Collector 1F, successive changes after placement. Two replacement volumes (28 hours at 0.7 μm/s) were necessary to reach groundwater concentrations. Orthophosphate levels differed in the two collectors but ammonia concentrations were quite similar after about one day (Figure 7). Total phosphate levels were similar on all sampling dates (Appendix; Collector 1E and 1F); nitrite and nitrate nitrogen from the collectors were generally less than 0.002 and 0.006 mg/liter, respectively.

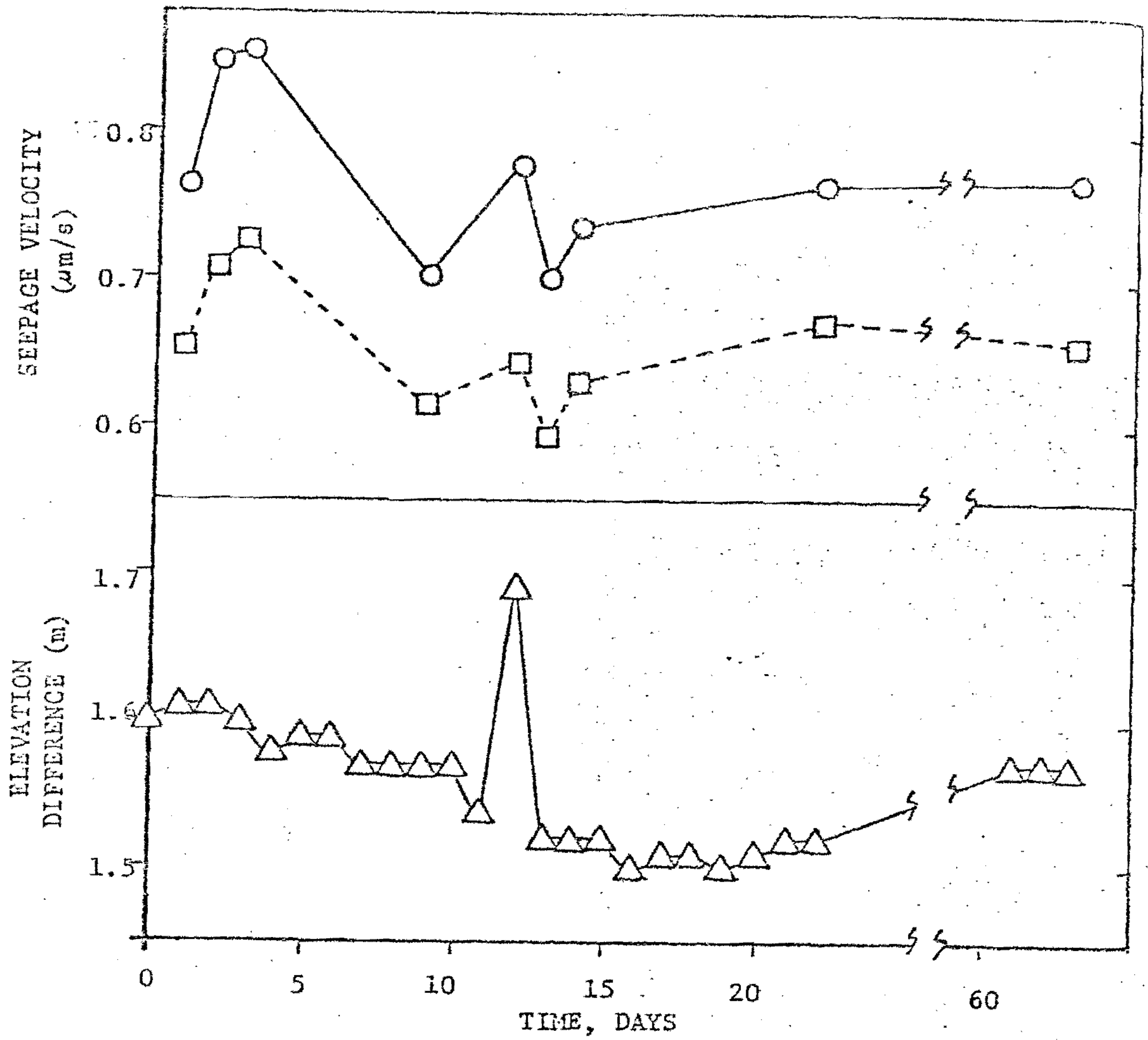


Fig. 6.—Seepage velocity measurements from two seepage collectors set 0.15 m apart and relative elevations of Lakes Sallie and Muskrat. Collector 1E was set several days before Collector 1F.

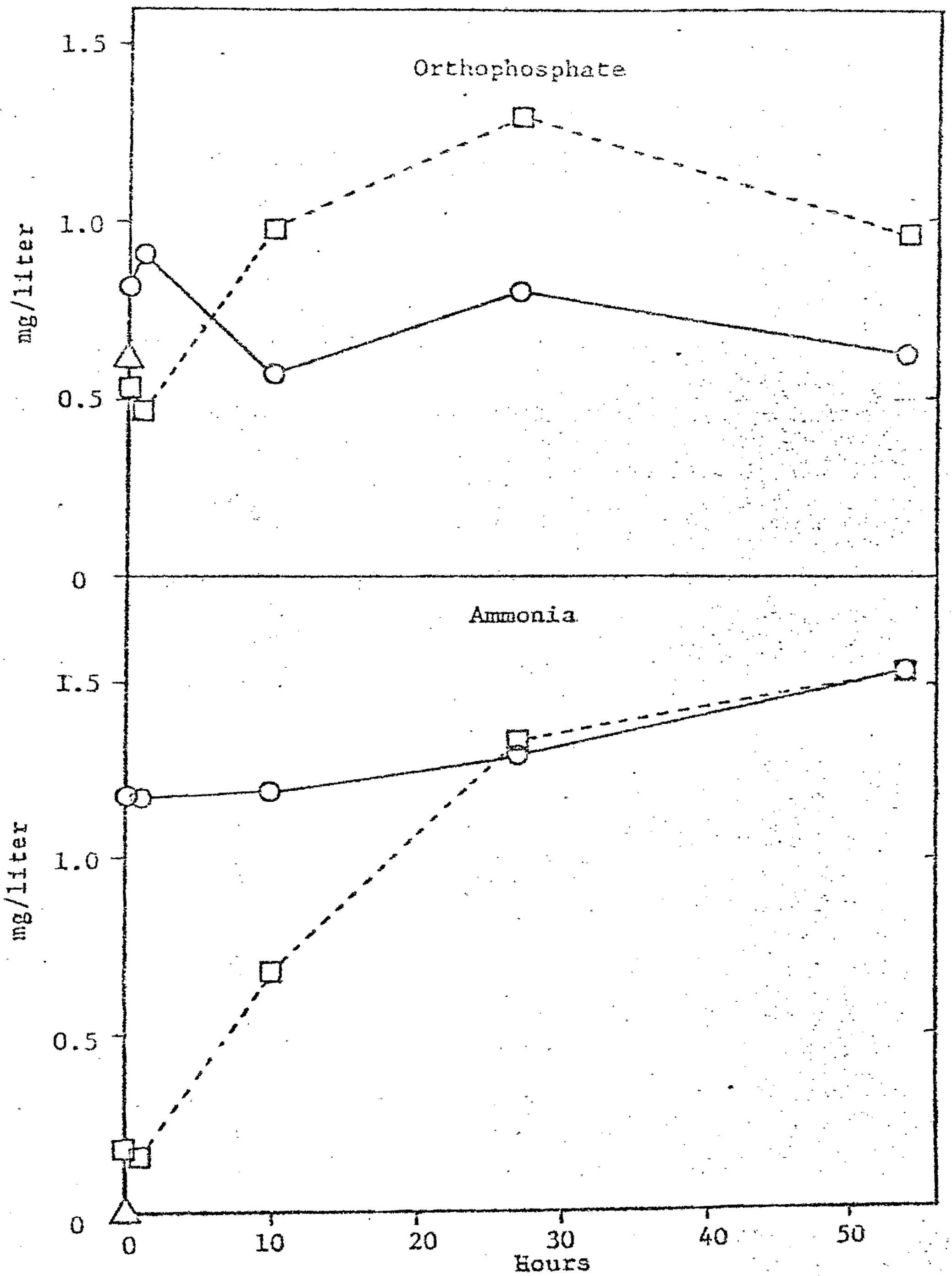


Fig. 7.—Orthophosphate and ammonia nitrogen concentration in water from two seepage collectors set 0.15 m apart. Collector 1E (-○-) was set several days before Collector 1F (-□-). Lake concentrations are indicated by △.

A well, driven 0.75 m into the water table 2 m back from the shoreline, gave water chemically similar to that from seepage collectors and distinct from lake water (Table 9).

TABLE 9

COMPARISON OF SEEPAGE, WELL, AND LAKE WATER NEAR THE FISH HATCHERY AT LAKE SALLIE

	Collector 1E[a]	Collector 1F[a]	Well[b]	Lake[c]
Orthophosphate, mg/liter	1.25	0.81	0.84	0.62
Total phosphate, mg/liter	1.51	1.68	1.58	1.40
Ammonia nitrogen, mg/liter	1.35	1.29	1.17	0.01
Nitrite nitrogen, mg/liter	0.001	0.000	0.000	0.000
Nitrate nitrogen, mg/liter	0.004	0.003	0.005	0.003

[a]Sampled 29 June 1971

[b]Sampled 26 June 1971

[c]Sampled 28 June 1971

Problems

Most problems encountered in measuring seepage were due to improper placement of the collector (Figure 8). Plugging of the vent tube sometimes occurred in areas where sediment accumulated; this was prevented by extending the opening with about 10 cm of pipe. Occasionally plugging resulted from growth of algae and necessitated periodic examination and cleaning.

Distribution and Nutrient Content of Seepage Inflow

A preliminary survey was made to locate seepage inflow areas along the lake margin as a guide to later work (Figure 9).

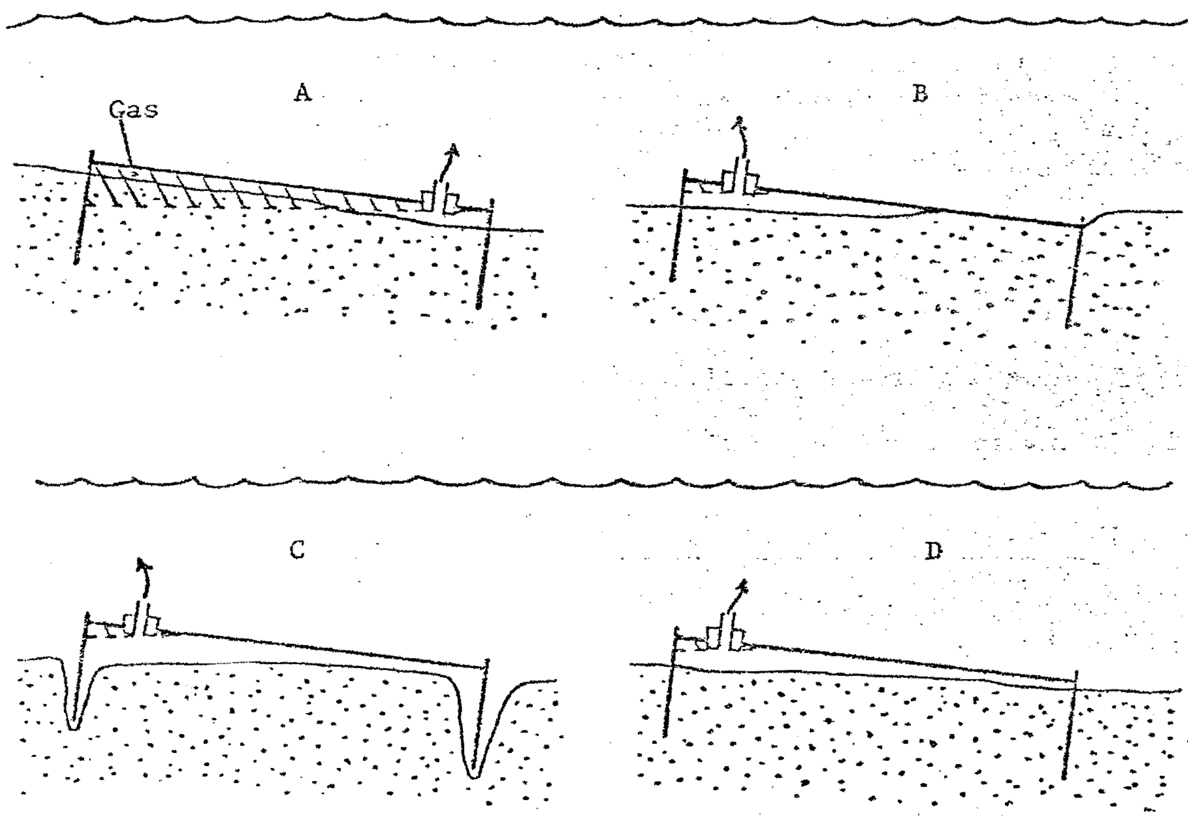
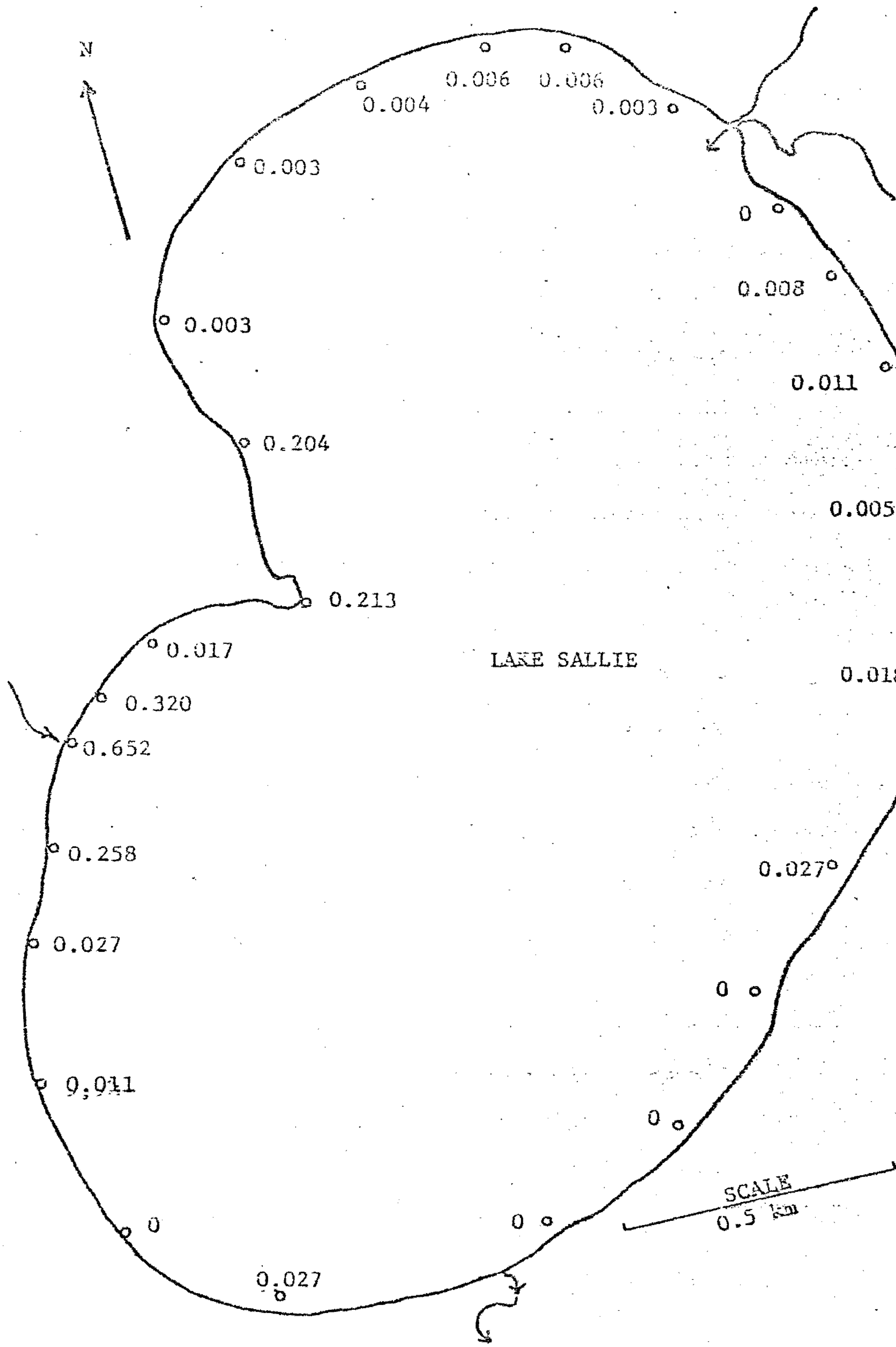


Fig. 8.—Possible failures of the seepage collector: a. collector not placed with hole near highest point, gas from sediment accumulates and reduces seepage; b. collector placed too far into lake bed, effective area reduced; c. collector pushed too rapidly into sediment, leakage through "blowouts"; d. correct installation.

Fig. 9.--Results of preliminary search for ground-water inflow areas, 10 to 24 October 1970. Numbers indicate velocity as μm/s. Each point represents one to four measurements at the same collector.


N
0.006
0.006
0.004
0.003
0.003
0
0.008
0.003
0.011
0.204
0.005
0.213
0.017
LAKE SALLIE
0.018
0.320
0.652
0.258
0.027
0.027
0
0.011
0
SCALE
0.5 km
0
0
0.027

Winter Sampling

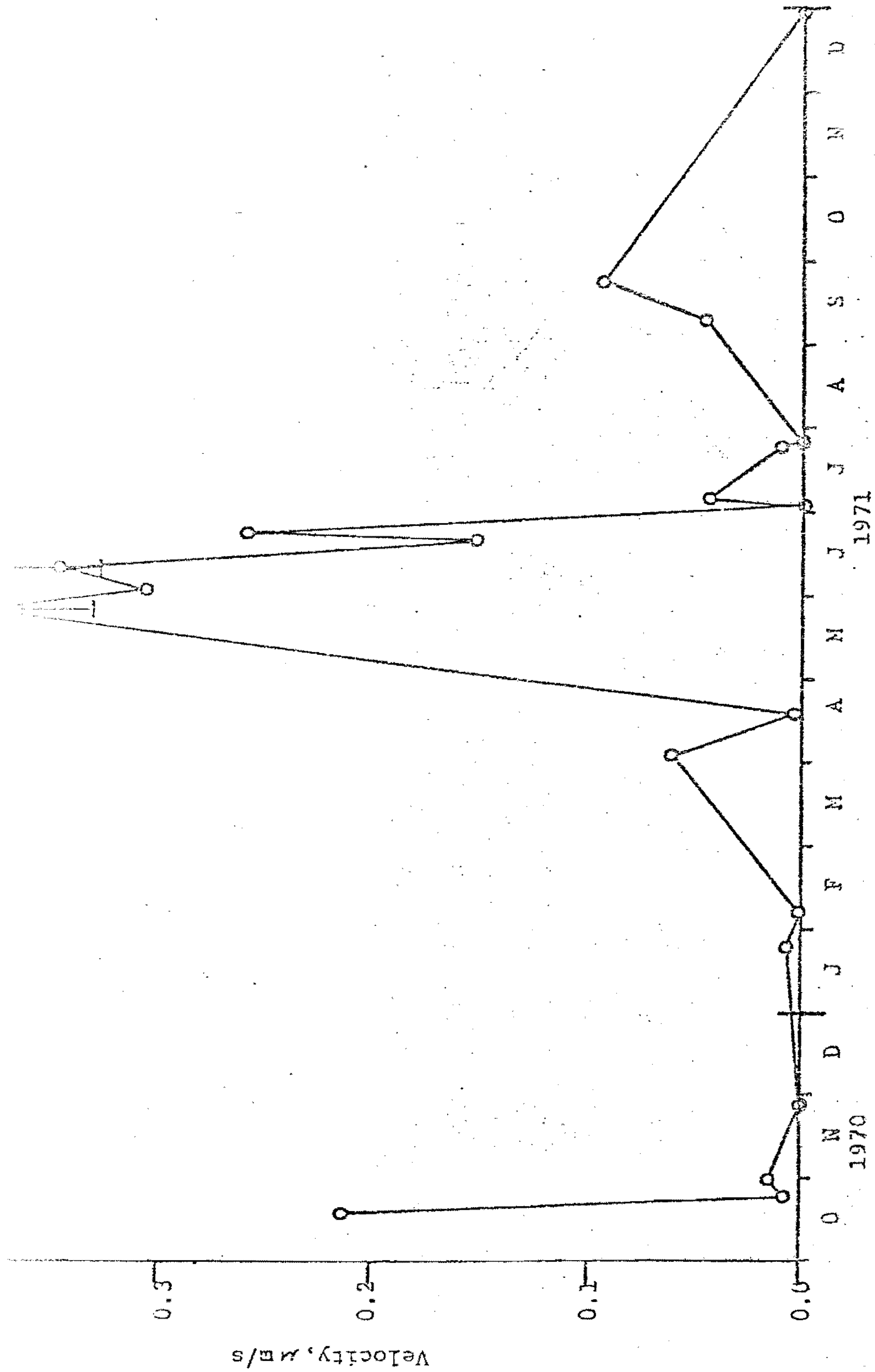
During the winter of 1970 and 1971, eleven seepage collectors were monitored in Lake Sallie and one in Lake Melissa (Figure 10, Collectors 1 through 9). Seepage rate at several collectors (2, 3B, 7, 8, and 9) was never greater than 0.035 μm/s and was frequently zero (Appendix). Seepage rate at other collectors (1A, 4, 5A and 6) was occasionally very low, but this may have been due to poor connections made through ice cover. Collector 3A, where visual observation was possible in the shallow water, had distinct seasonal variation, reaching peaks in spring, early summer, and again in fall (Figure 11). Gradual springtime increases in seepage velocity were measured at Collectors 4 and 6 (Appendix). Two measurements in May, 1972, suggested that groundwater inflow increases two to three-fold in spring.

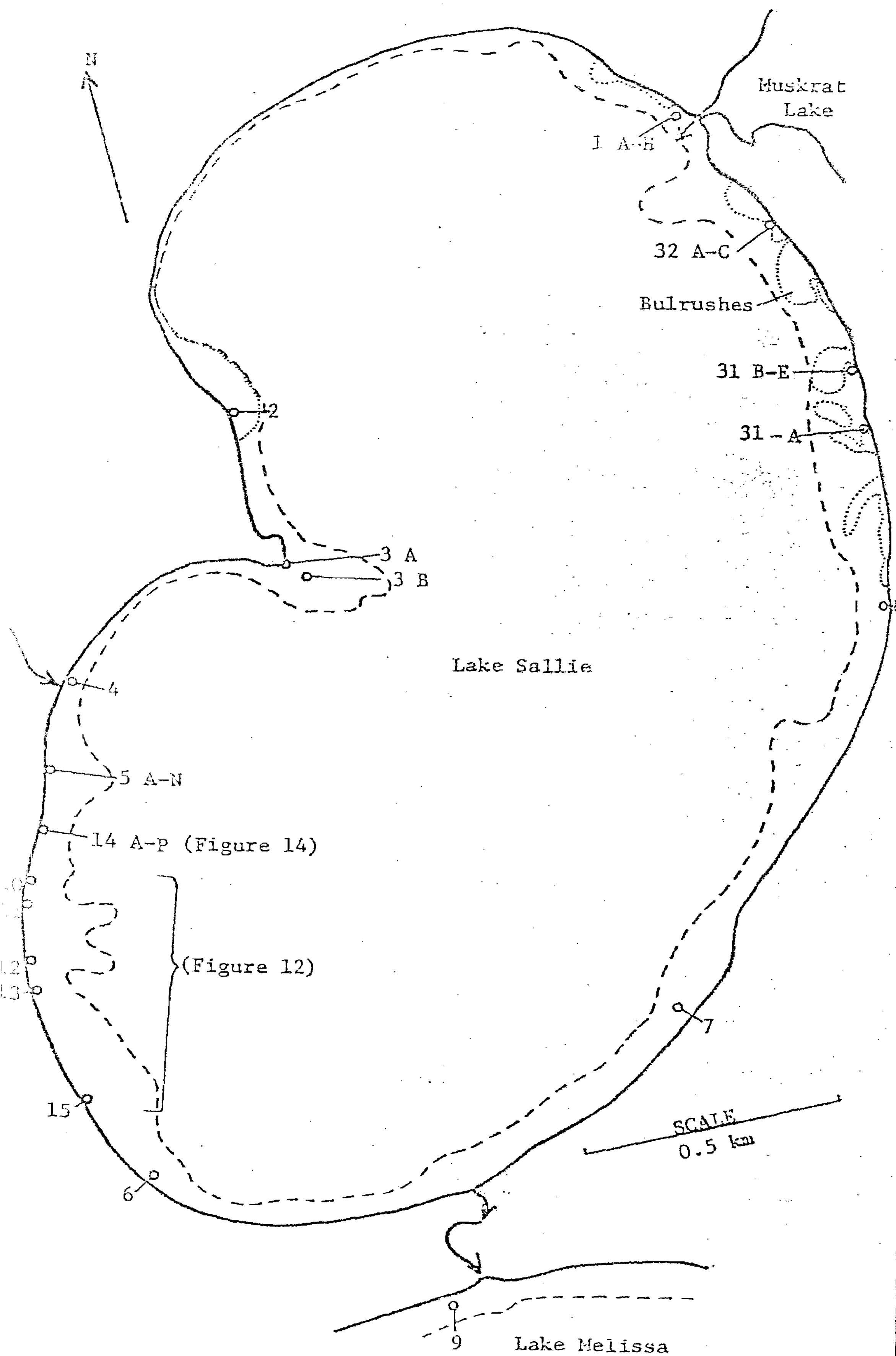
At one location (Appendix; Collector 5A) there was a decrease in orthophosphate from September to January, but seasonal changes in seepage chemistry were rare. At Collector 3A there was an inverse relation between nutrient concentration and velocity, i.e. when velocity was low, phosphorus and nitrogen were high. Orthophosphate ranged from 3.67 to 0.17 mg/liter and ammonia from 8.88 to 0.96 mg/liter (Appendix).

Southwestern Shore

Seepage distribution was studied along an 800 m segment of the southwestern shore from June through December, 1971 (Figure 12). Inflow was most rapid near shore and decreased exponentially with distance into the lake (Figure 13) except on Transect II where seepage was most rapid 17 m offshore. No significant changes in velocity were observed over the six-month period.

Fig. 10.--Seepage stations on Lakes Sallie and Melissa. Only the 1.5 m contour line is shown.


Velocity, μm/s
0.0
0.1
0.2
0.3
O
N
1970
D
J
F
M
A
M
J
J
1971
A
S
O
N
D


N
Muskrat
Lake
1 A-H
32 A-C
Bulrushes
31 B-E
31 - A
2
3 A
3 B
8
Lake Sallie
4
5 A-N
14 A-P (Figure 14)
12
13
(Figure 12)
7
15
SCALE
0.5 km
6
9
Lake Melissa

?.--Southwestern Lake Sallie study area. The 1.5 m and lines are shown.

nd:

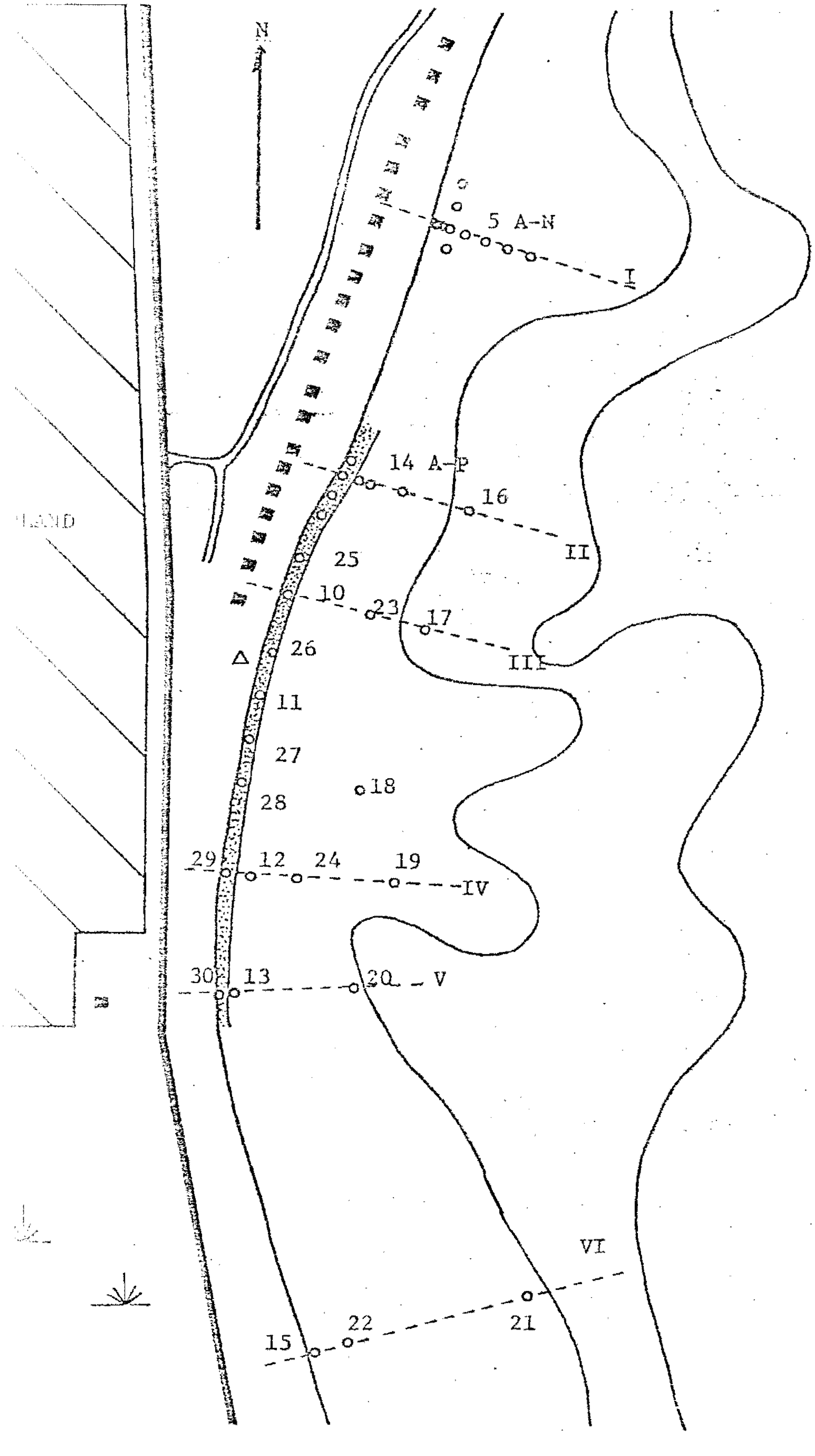
= house

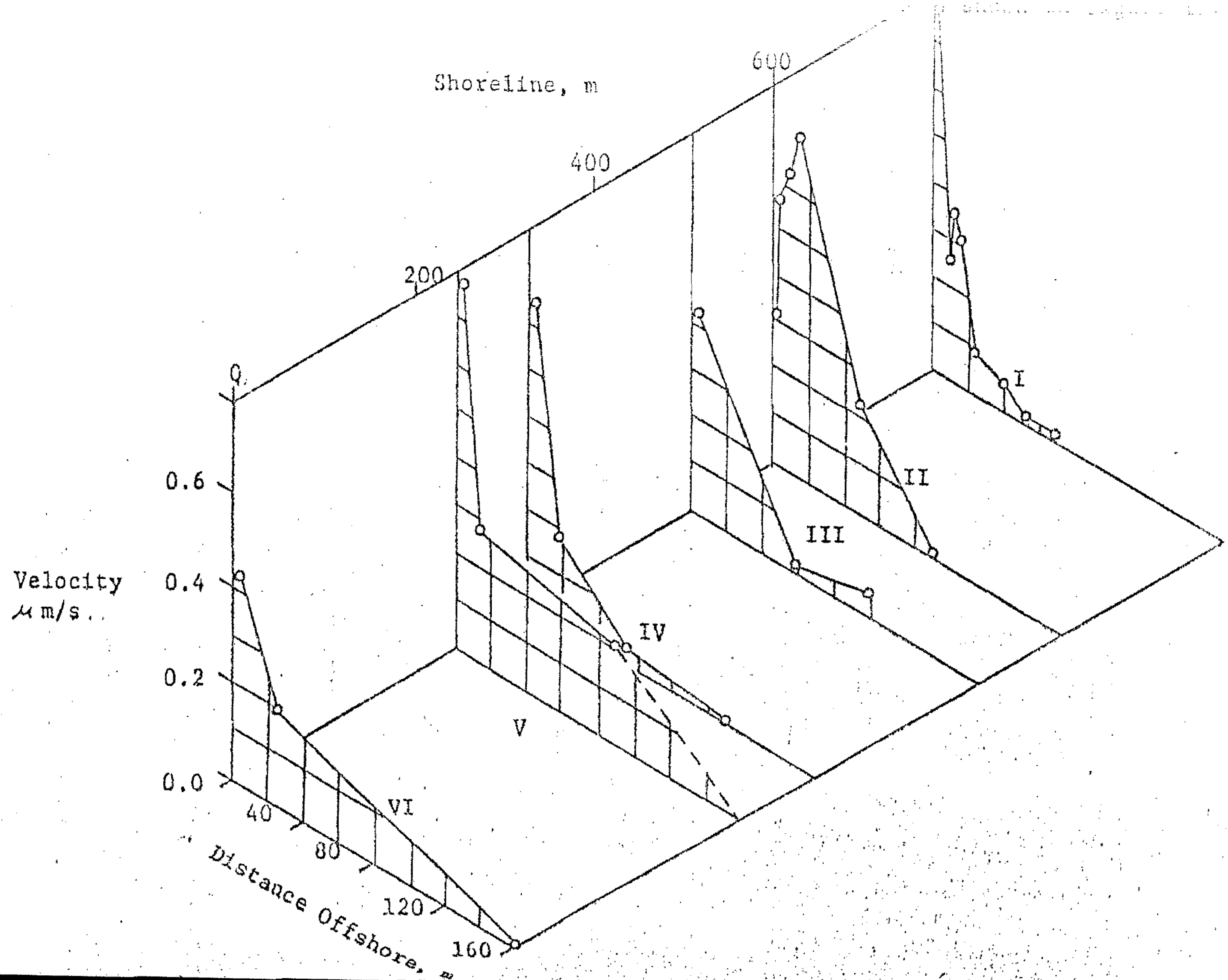
= seepage measurement point

= high nitrate zone referred to in text

= transect number

= United States Geological Survey well


N
5 A-N
I
14 A-P
16
II
25
10
23
17
III
26
11
27
18
28
29
12
24
19
IV
30
13
20
V
VI
22
15
21
LAND



Shoreline, m
0
200
400
600
Velocity
μ m/s
0.6
0.4
0.2
0.0
40
80
120
160
Distance Offshore, m
I
II
III
IV
V
VI

Seepage inflow along the 800 m segment was calculated by finding the volume beneath the curves shown in Figure 13. This was done by multiplying the average area beneath adjacent curves by the distance between them and adding these partial volumes. The groundwater inflow over the 0.13 km^2 area was 4.50 x 10^5 m^3/year (364 acre-ft/yr), 30% of this within 8 m of the shoreline.

A large nitrate input (2.19 to 50.4 mg/liter at about 0.466 μm/s, (Figure 12 and Appendix) occurred within 8 m of the shoreline between Transects II and V. Outside this area, average nitrate concentrations were less than 0.022 mg/liter in the seepage inflow. The high nitrate zone supplied 37% of the total inorganic nitrogen of the 0.13 km^2 area between Transects I and VI, but only 12% of the inflow (Table 10). Nitrogen was predominantly in the form of nitrate.

Ammonia nitrogen in excess of 3 mg/liter was present in initial samples from Collectors 5G, 14P, 15, and 22 (Appendix). Orthophosphate ranged from 0.08 to 2.2 mg/liter and total phosphate from 0.12 to 3.75 mg/liter (Appendix). Relatively large sample-to-sample variations in phosphate concentration occurred (Appendix) and no pattern emerged. In one instance, concentration of total phosphate increased with distance from shore (Collectors with prefix 5, Appendix).

Northeastern Shore

Inflow was irregularly distributed along this shore as indicated by both preliminary measurement (Appendix) and sediment temperature, which varied from 21 C (same as lake) to 11 C along a 200 m stretch of shore within 10 m of shore on 16 June 1971. Where seepage velocity was greater than about 0.8 μm/s, I could feel the difference between lake

TABLE 10

COMPARISON OF HIGH-NITRATE ZONE TO THE REMAINDER OF THE AREA BETWEEN TRANSECTS I AND VI, FIGURE 12

Parameter	High-Nitrate Zone	Remainder of Area	Per Cent of Total in High-Nitrate Zone
Area, m^2	3,650	127,000	3
Discharge (June through December 1971), m^3	26,800[a]	198,000[b]	12
Orthophosphate, kg	7.75 (0.29)[c]	107 (0.54)	7
Total Phosphate, kg	12.0 (0.45)	230 (1.16)	5
Ammonia Nitrogen, kg	17.4 (0.67)	250 (1.26)[d]	7
Nitrite Nitrogen, kg	3.58 (0.134)	0.2 (0.001)	64
Nitrate Nitrogen, kg	129 (4.83)	1.2 (0.006)	99
Total Inorganic Nitrogen, kg	150 (5.63)	251 (1.27)	37

[a]Calculated as the product of average velocity (0.466 μm/s) and area.

[b]Calculated by difference (i.e., 2.25×10^5 minus 2.68×10^4 for the six-month period).

[c]Parentheses indicate average concentration as mg/liter.

[d]Single determinations were not included in this average.

and sediment temperature. The two collectors (31E and 32C) were within 10 m of shore, probably in the path of shallow groundwater and in separate inflow areas. Compared to Collector 31E, Collector 32C had greater flow and nutrient concentration (Appendix).

Tracer Study

Site Description

A septic tank was selected that met the following criteria: 1) year-round use, 2) location on a shore with rapid, evenly distributed seepage inflow, 3) typical design, and 4) location near the shoreline. The installation had a 3.8 m^3 (1,000 gallon) settling tank, a smaller distribution tank, and a small area of broken concrete block which received the effluent (Figure 14). The point of discharge was about 16 m (50 ft) from the water's edge. From 1949 through 1967, the house had two summer residents, but since 1968 has had six year-round residents. The tank received about 0.76 m^3 (200 gallons) of domestic sewage daily, but no laundry waste.

The septic tank was surrounded by clean, brown sand with grains from 0.1 to 1 mm diameter, containing less than 1% clay and silt, and a few pebbles up to 3 cm diameter. Porosity was roughly 40%. A well log, 200 m southwest, showed that the clean sand extended 7 m below the water table to a relatively impermeable clay and silt layer (McBride, 1972b). Distances wells penetrated the water table are shown in Table 11.

Nutrient Output of Septic Tank

Phosphate and ammonia nitrogen were present in the septic tank (Table 12). At 0.76 m^3 discharge per day, this tank released 8 kg

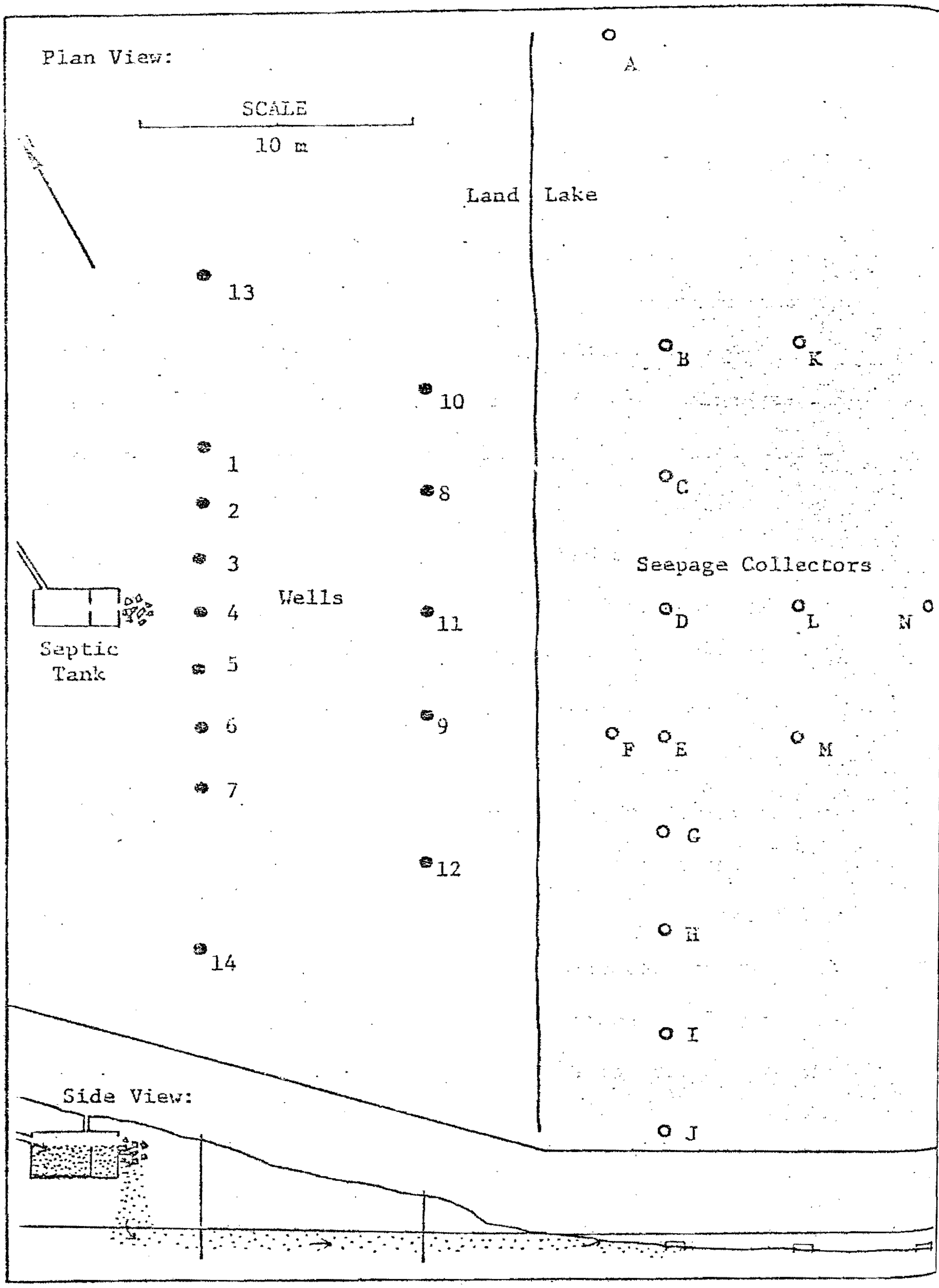


Fig. 14.--Septic tank study site, station 14.

(18 lbs) of phosphorus and 58 kg (130 lbs) of nitrogen to soil and groundwater each year.

TABLE 11

WATER TABLE PENETRATION OF WELLS AT STATION 14

Well	Penetration, m	Well	Penetration, m
1	1.77	8	1.85
2	—	9	1.72
3	1.34	10	1.83
4	1.34	11	1.95
5	1.24	12	2.11
6	1.29	13	—
7	1.37	14	1.57

TABLE 12

NUTRIENT CONTENT OF THE SEPTIC TANK AT STATION 14

	Date	
	15 August	27 November
orthophosphate (mg PO_4/liter)	90	82
total phosphate (mg PO_4/liter)	91	83
Ammonia (mg N/liter)	217	204
Nitrite (mg N/liter)	0.000	0.000
Nitrate (mg N/liter)	0.000	0.000
Specific Conductivity (μmhos/cm)	19,500**	1,900
Chloride (mg Cl/liter)	—	161

**After adding 45 kg of NaCl

Nutrient concentrations in nearshore seepage in the uninhabited area 125 to 360 m south (Collectors 11, 26, 28, 29, and 30; Figure 12) were used as background levels: 0.42 mg/liter total phosphate and 4.01 mg/liter total inorganic nitrogen.

Tracer

After 25 days salt tracer reached Well 5; Wells 3, 4, and 6 after 56 days; and Wells 1, 7, 8, and 9 after 91 days (Figures 15 and 16). This indicated a groundwater velocity of 2.0 μm/s (0.43 ft/day). Increases occurred at Collectors G and H after 56 days, and at collectors E and F after 70 days (Figure 17). Well data suggests that increases at Collectors G and H did not mark the arrival of tracer. Conductivity decrease on 1 October was probably caused by freezing of samples.

Tracer indicated that Wells 5 and 9 and Collectors E and F were located in the major flow path. The effluent fanned out and caused chloride and conductivity increases at wells to the right and left suggesting that it reached the lake in a longshore band at least 30 m long. Slowness of salt reaching Wells 4 and 11 indicated that this central area was partially clogged.

The groundwater was warmed at Wells 4, 5, 9, and 11, indicating that temperature might be a useful indicator of septic-tank discharge. Hydrogen ion concentration (pH) however did not indicate effluent flow (Figure 18). With the passage of tracer, chloride levels changed by as much as ten times (e.g., Well 5: 74.2, 770, 182 mg/liter), but specific conductivity varied by less than two times (e.g., Well 5: 1418, 2780, 1455 μmhos/cm).

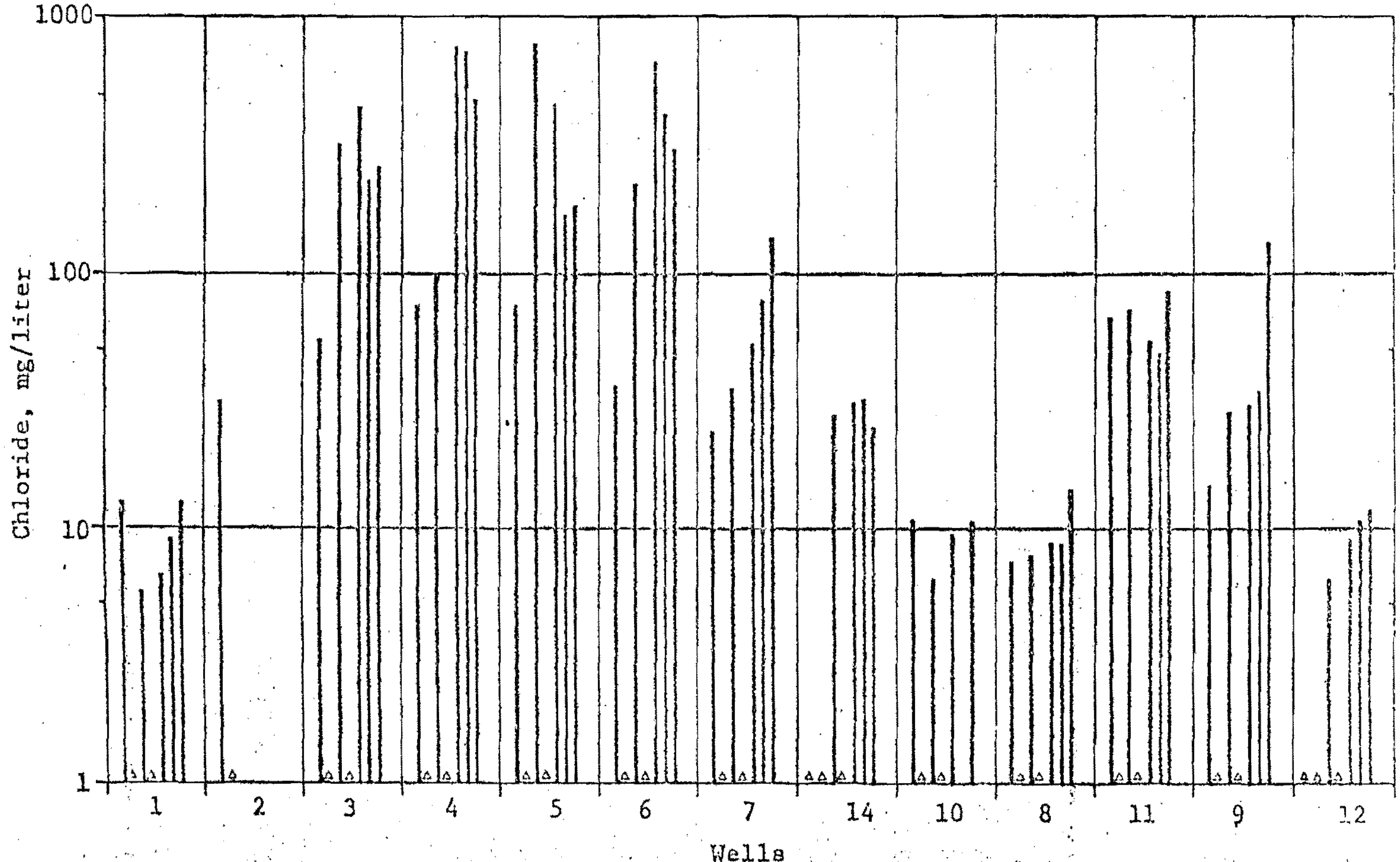


Fig. 15.--Chloride concentration for wells at Station 14. Bars for each measurement site are in chronological order: 28 August; 17, 25 September; 1, 23 October; 6, 27 November, 1971. Small Δ denotes missing data.

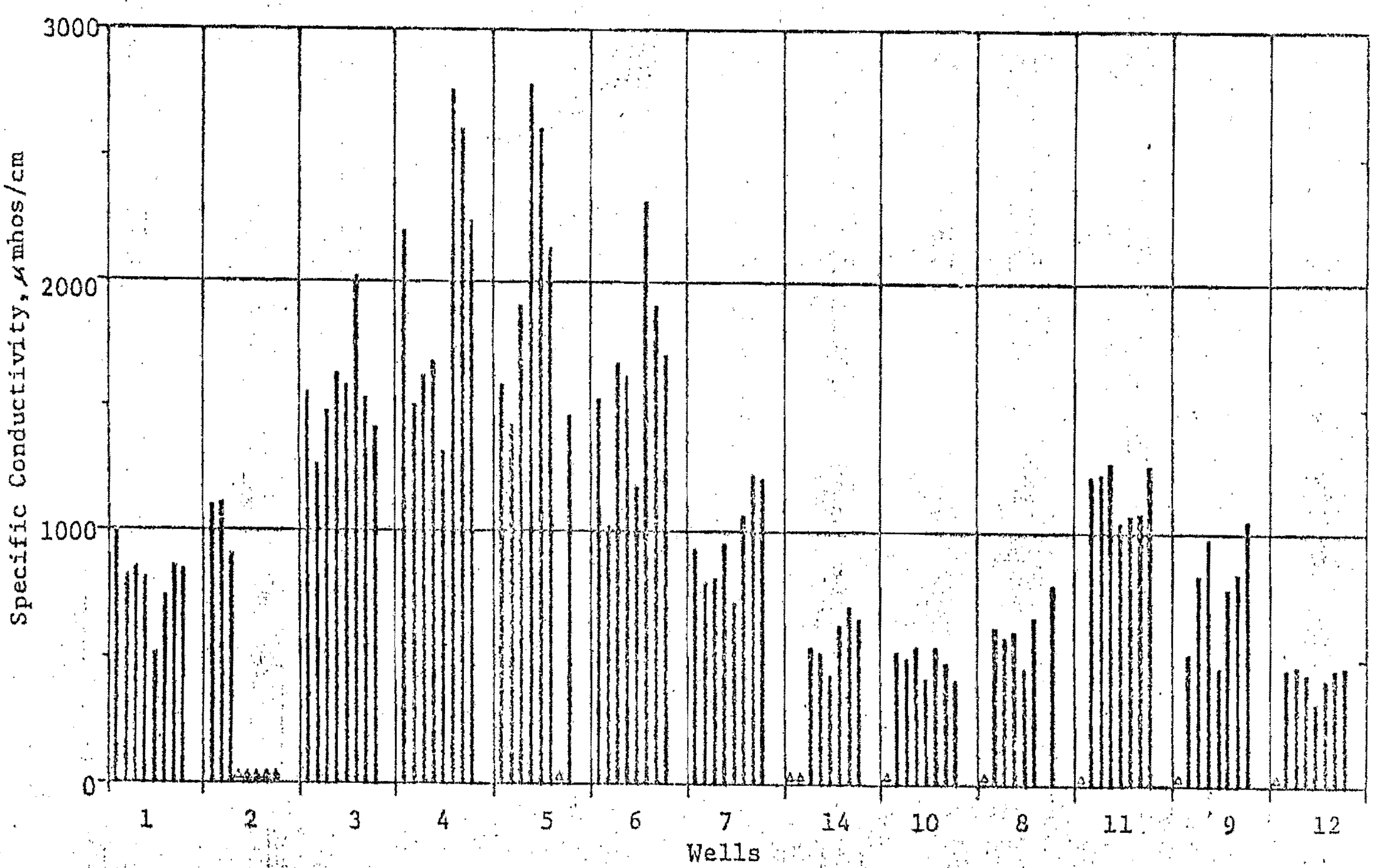


Fig. 16.--Specific conductivity for wells at Station 14. Bars for each measurement site are in chronological order: 12, 25 August; 17, 25 September; 1, 23 October; 6, 27 November. Small Δ denotes missing data.

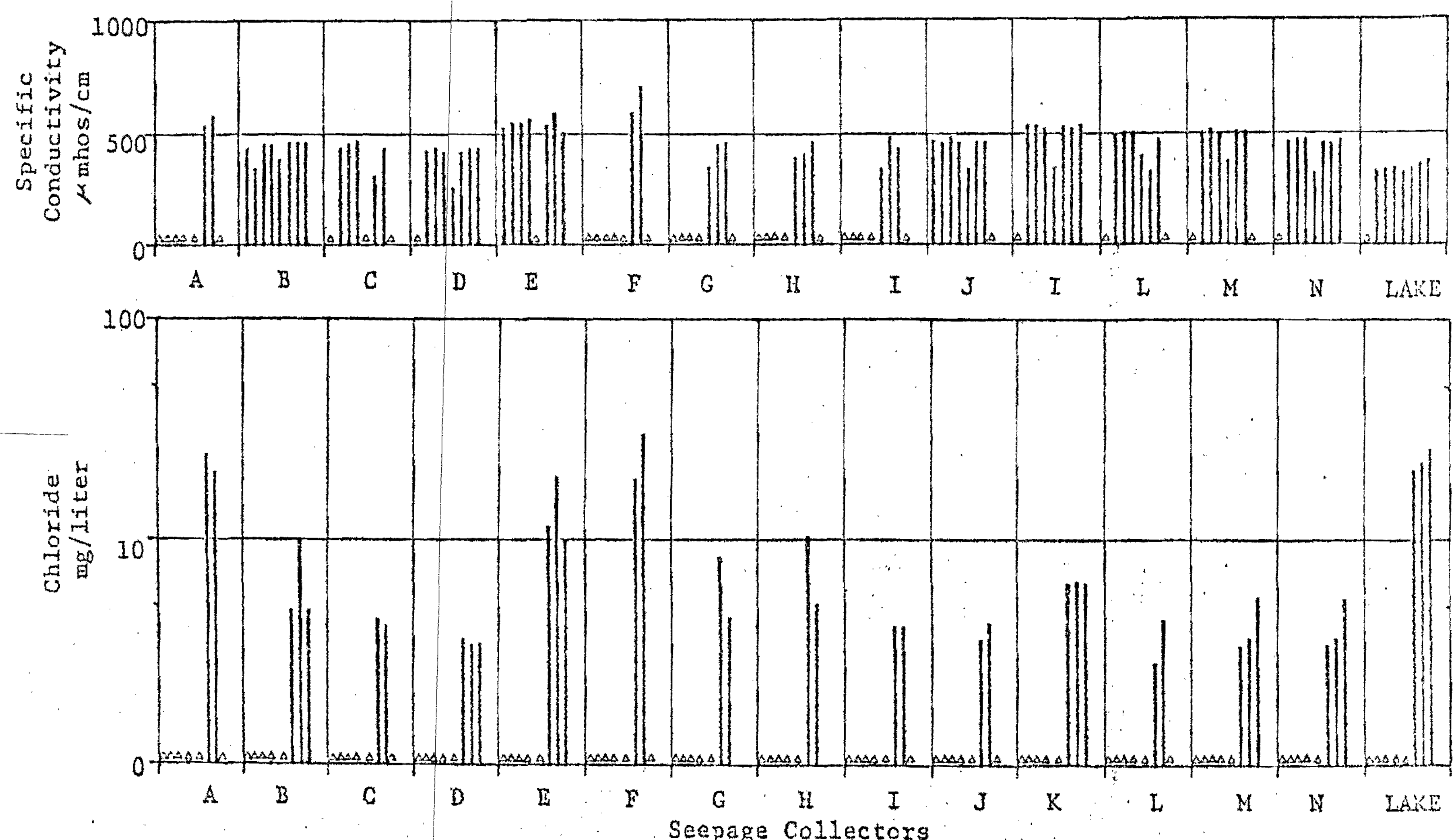


Fig. 17.--Chloride concentration and specific conductivity for seepage collectors and lake at Station 14. Bars for each measurement are in chronological order: 28 August; 11, 17, 24 September; 1, 23 October; 6, 27 November, 1971. Small Δ denotes missing data.

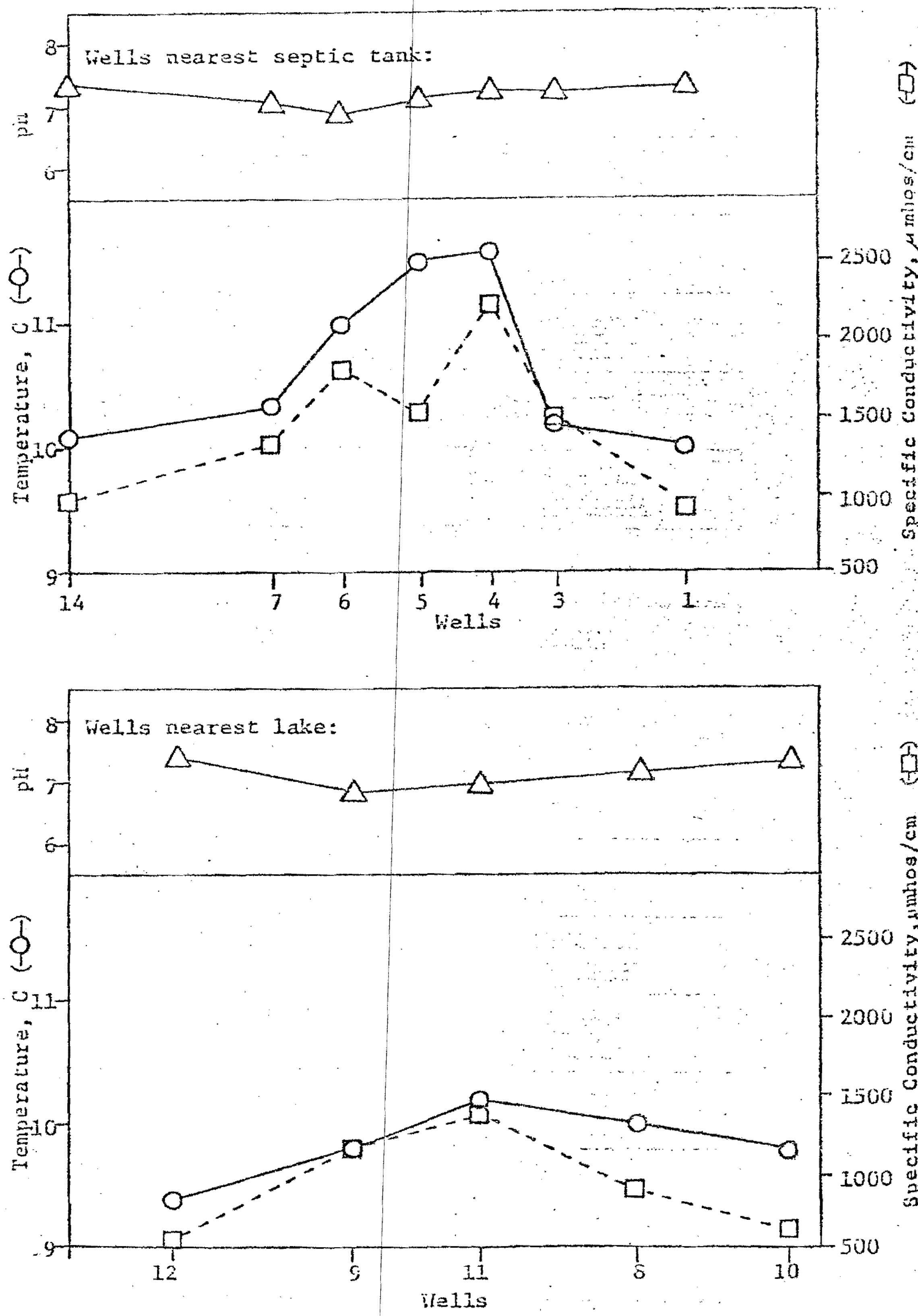


Fig. 13.--Temperature, specific conductivity, and pH for wells at Station 14, 27 November 1971.

Nitrogen

Ammonia levels were extremely high at Well 4, nearest the discharge point, and generally decreased on either side of a line between Wells 4 and 11 (Table 13). In the seepage inflow, ammonia was conspicuously high (more than 1 mg/liter) at Collectors E, G, H, I (Appendix, Collectors with prefix 14).

Nitrate levels were generally highest at Well 5 in the first row and at Well 9 in the second row and decreased with distance from the septic tank. Concentrations in the second row of wells were roughly half the concentration in the first row. This was probably due to lateral spreading, sorption, and the slightly deeper penetration of the wells in the second row. Well 4 had relatively low nitrate values compared to wells on either side of it; this possibly due to partial clogging and resulting anaerobic conditions which would inhibit nitrification.

With few exceptions, nitrate nitrogen levels in nearshore seepage was greater than 1.5 mg/liter and ranged up to 50.4 mg/liter (Appendix, Collectors with prefix 14). Exceptions occurred in initial samples probably before the Collector had become completely flushed, or where flow was low (e.g., Collector H with 0.1 μm/s). Further than 9 m from shore, nitrate was less than 0.009 mg/liter as noted previously.

Ammonia appeared to be rapidly oxidized to nitrate near the septic tank (Figure 19). Background ammonia levels were reached within 15 m. Nitrate levels did not increase with distance; this suggested that nitrification was offset by denitrification, dilution, or sorption. Maximum nitrate levels may have been attained as the effluent moved down to the water table.

TABLE 13

CHEMICAL ANALYSIS OF WELL WATER AT STATION 14

Date	Well	mg PO_4/liter		mg N/liter		
		Orthophosphate	Total Phosphate	Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
11 August	1	0.51	—	1.29	0.562	21.3
	2	0.10	—	1.45	0.185	23.7
	3	0.35	—	0.96	0.300	52.8
	4	0.72	—	85	0.280	17.9
	5	0.49	—	3.2	0.437	57.2
	6	0.25	—	1.08	0.537	40.4
	7	0.10	—	1.12	0.450	20.6
24 August	1	0.20	7.90	1.87	0.506	22.3
	2	0.26	3.91	1.37	0.454	45.0
	3	0.45	8.30	1.44	0.612	48.2
	4	0.11	34	81	0.808	27.3
	5	0.55	16.5	3.5	0.498	68.4
	6	0.38	3.68	1.27	0.364	32.8
	7	0.52	6.75	1.74	0.290	11.8
	8	0.36	—	0.20	0.12	13.0
	9	0.56	—	0.14	0.09	10.0
	10	0.20	9.86	0.45	0.221	13.9
	11	0.54	6.40	2.21	0.64	35.7
	12	0.27	6.98	0.24	0.127	10.4
17 September	1	0.77	3.20	1.58	0.398	24.3
	2	0.26	2.14	1.03	0.232	32.8
	3	0.35	2.76	4.0	0.764	35.9
	4	2.46	38.6	90	1.8	18.4
	5	0.52	15.8	5.2	0.739	62.2
	6	0.32	2.00	2.24	0.434	64.6
	7	0.29	2.14	1.76	0.567	26.8
	8	0.31	4.88	0.73	0.254	14.2
	9	0.27	4.96	0.69	0.278	36.3
	10	0.29	2.76	0.61	0.134	9.48
	11	0.29	3.12	3.8	0.224	31.3
	12	0.10	2.28	0.19	0.046	9.19
	13	0.19	0.37	0.37	0.178	15.6
	14	0.14	2.67	0.27	0.111	9.55
25 September	1	0.61	3.62	1.53	0.341	18.9
	3	0.19	2.26	1.67	0.942	37.5
	4	5.2	56	142	0.443	4.44
	5	0.33	14.8	6.70	0.250	60.4
	6	0.34	1.50	2.19	0.345	58.5
	7	0.40	1.78	2.24	0.690	36.6

TABLE 13--Continued

Date	Well	mg PO_4/liter Orthophosphate	mg PO_4/liter Total Phosphate	mg N/liter Ammonia Nitrogen	mg N/liter Nitrite Nitrogen	mg N/liter Nitrate Nitrogen
25 September (Continued)	8	0.42	3.66	0.82	0.286	12.1
	9	0.45	2.86	0.99	0.217	35.4
	10	0.35	3.78	0.45	0.097	10.3
	11	0.42	2.46	3.71	0.348	28.4
	12	0.25	2.12	0.45	0.174	8.3
	14	0.42	4.02	1.08	0.179	7.8
1 October*	1	0.19	3.64	2.10	0.358	14.5
	3	0.09	2.36	3.96	0.910	44.0
	4	0.61	34.6	97	0.167	2.40
	5	0.13	12.0	5.6	0.702	57.7
	6	0.10	1.34	2.14	0.481	48.0
	7	0.06	2.4	1.91	0.496	29.9
	8	0.10	4.60	0.80	0.208	10.7
	9	0.23	1.66	0.27	0.054	11.5
	10	0.24	4.10	0.52	0.130	9.74
	11	0.24	1.38	2.86	0.234	40.3
	12	0.09	1.70	0.16	0.338	8.80
	14	0.07	9.70	1.27	0.119	8.27
23 October	1	0.39	2.64	2.45	0.473	13.4
	3	0.36	2.00	7.4	0.987	51.8
	4	3.72	83	138	0.121	5.98
	5	0.36	7.08	5.7	0.598	61.1
	6	0.48	1.74	5.3	0.355	46.6
	7	0.22	2.70	3.45	0.819	38.2
	8	0.59	4.38	1.57	0.318	10.8
	9	0.64	4.28	0.43	0.062	17.9
	10	0.11	2.54	0.83	0.095	10.8
	11	0.44	2.90	3.97	0.247	25.0
	12	0.21	1.98	0.35	0.032	6.23
	14	2.02	5.74	0.78	0.094	7.14
7 November	1	0.20	2.86	2.21	0.294	20.6
	3	0.51	2.00	3.84	0.114	49.4
	4	2.67	74	137	0.157	4.42
	5	0.36	--	3.5	0.65	61.1
	6	0.17	1.44	2.33	0.291	63.4
	7	0.26	1.44	2.7	0.377	27.3
	8	0.20	7.20	3.2	1.00	2.14

TABLE 13—Continued

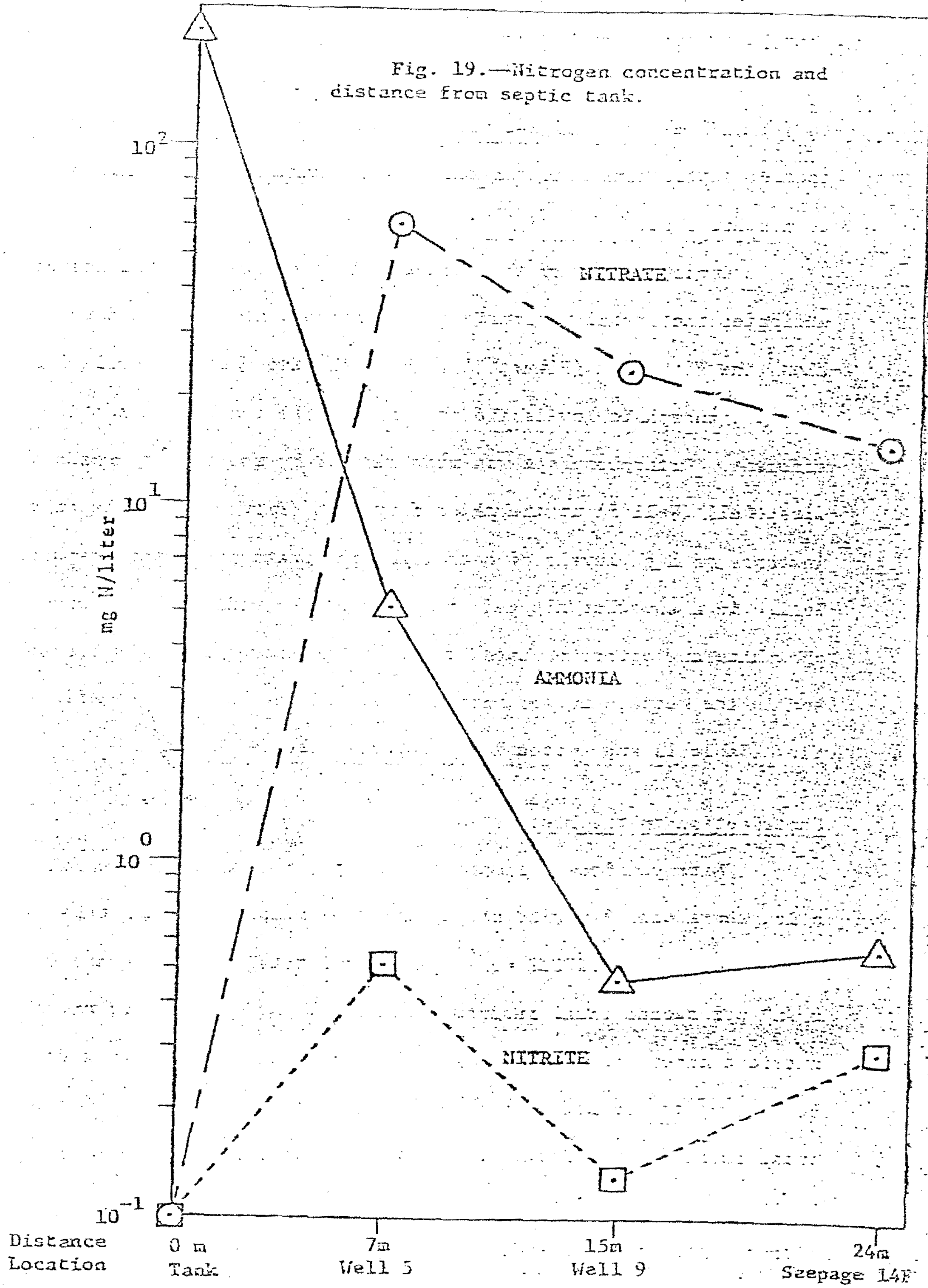
		mg PO_4/liter		mg N/liter		
Date	Well	Orthophosphate	Total Phosphate	Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
7 November (Continued)	9	0.86	2.46	0.32	0.064	27.4
	10	0.44	2.8	0.80	0.135	10.4
	11	0.58	3.34	3.6	0.187	28.8
	12	0.16	2.46	0.42	0.049	7.07
	14	0.56	3.56	0.85	0.182	8.83
27 November	1	0.15	2.20	3.2	0.295	6.00
	3	0.15	1.50	3.48	0.276	44.0
	4	7.75	77.6	130	0.128	3.86
	5	2.49	12.2	6.8	0.104	57.6
	6	0.18	1.34	2.21	0.448	56.8
	7	0.11	0.90	2.74	0.773	24.0
	8	0.14	2.20	2.13	0.533	24.0
	9	0.17	1.52	0.38	0.149	31.4
	10	0.14	2.48	1.08	0.143	12.3
	11	0.27	0.28	3.80	0.49	33.4
	12	0.00	2.04	0.70	0.149	11.5
	14	0.15	4.90	1.16	0.144	6.53

Phosphorus

Soluble orthophosphate averaged 2.19 mg/liter at Well 4 but ranged from 0.11 to 7.75 mg/liter (Table 13). Concentrations in all other wells were, with few exceptions, in the range 0.15 to 0.9 mg/liter. Higher values occurred once at Well 14 (2.02 mg/liter). Wells in the center of effluent flow (5 and 9) did not have higher orthophosphate concentrations than the other wells.

Total phosphate indicated both mineral and fixed phosphorus, because soil was included in the test. Values varied at each well (e.g., Well 10: 2.5 to 9.9 mg/liter) but this was probably due to varying amounts of soil removed at each sampling. Average total phosphate

Fig. 19.—Nitrogen concentration and distance from septic tank.



values at Wells 4 and 5 were 58 and 13 mg/liter respectively, but at other wells average total phosphate ranged from 1.9 mg/liter at Well 6 to 5.1 mg/liter at Well 14. Higher values at Well 14 may be due to another septic tank situated only 5 m landward of this well, but not used since 1968.

Consideration of the effluent flow as shown by the tracer indicates that total phosphate and orthophosphate decreased markedly along the flow path (Figure 20). With the exception of Wells 5 and 4, total phosphate levels did not appear affected by the septic tank effluent. Orthophosphate was much reduced by the time it reached the first well (Well 5) in the major flow path (Figure 20). The only instance of high levels of both total phosphate and orthophosphate was Well 4 in a somewhat clogged area nearest the effluent discharge. Total phosphate and orthophosphate levels in the second row of wells (8 to 12) and in the seepage inflow were not related to the trend of effluent flow (Table 13 and Appendix, Collectors prefixed by 14).

Contribution to the Lake

Nitrogen from the septic tank appeared to enter the lake through a longshore band 9 m wide and at least 30 m long. Within this band inflows averaged 0.00028 mg/m^2 per second total phosphate and 0.00486 mg/m^2 per second total inorganic nitrogen. By comparison, average nutrient input from the uninhabited shoreline 125 to 360 m south was 0.00023 mg/m^2 per second total phosphate and 0.00217 mg/m^2 per second total inorganic nitrogen. The difference in phosphate levels is probably below the limits of sampling error. For the 270 m^2 area, the nitrogen difference was 23 kg/year, an amount equivalent to 40% of that leaving the septic tank.

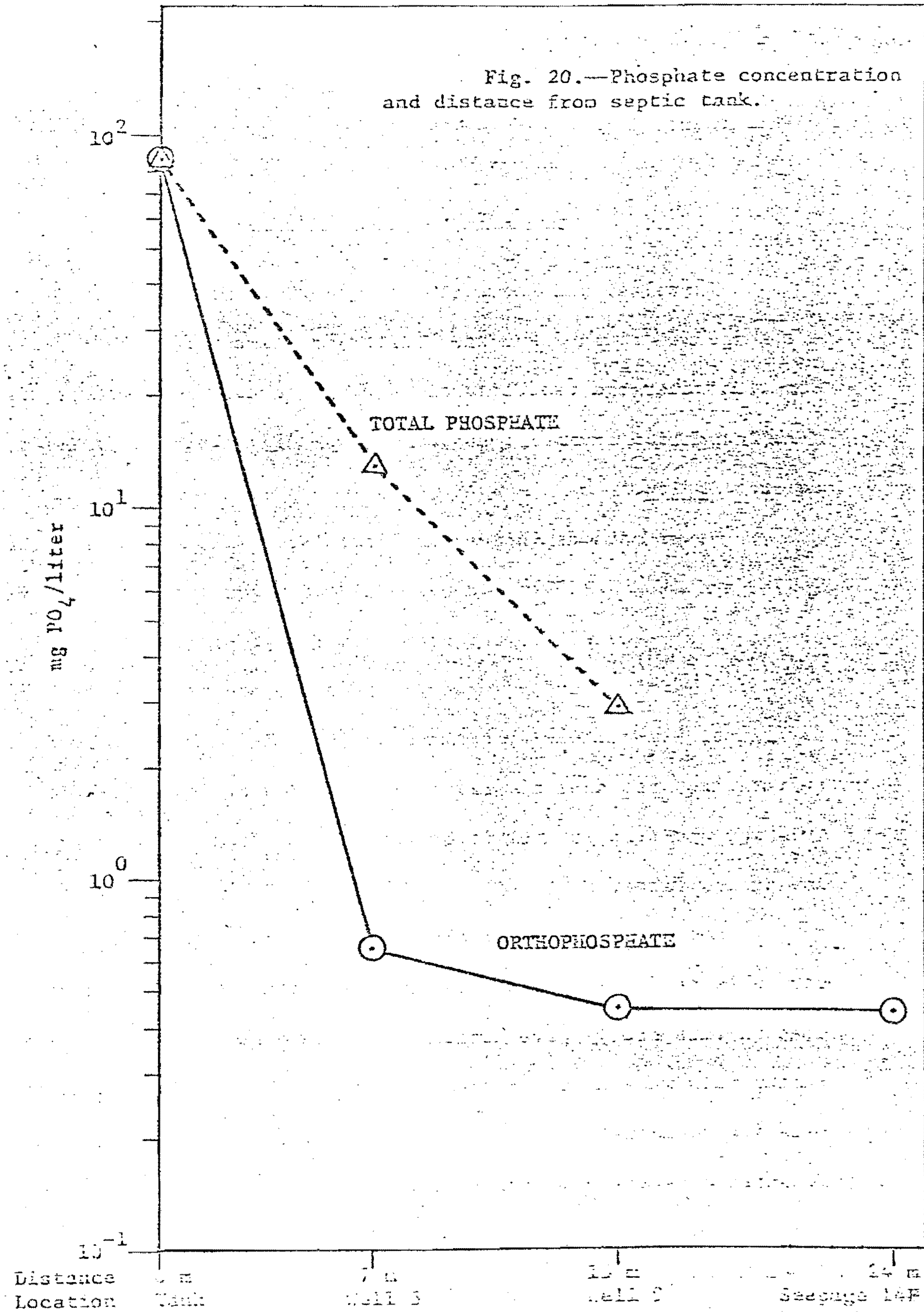


Fig. 20.—Phosphate concentration and distance from septic tank.

DISCUSSION

Performance of Seepage Collector

Israelson and Reeve (1944) were the first to report the use of a seepage meter employing the plastic-bag technique. They filled the bag with water and used loss of volume as a measure of seepage outflow from irrigation channels, and only later did Reeve (1971) use it to measure inflow.

Other methods (Bower and Rice, 1968; Warnick, 1951; McBride, 1972a; and Zuber, 1970) have been used to measure groundwater flow into or out of surface waters but none appear appropriate for sample collection. Warnick (1951) suggested that the accuracy of the plastic-bag technique, "is questionable since the thin-membrane [bag] offers some resistance," and does not maintain zero-flow potential across itself. This was not studied, but if anything, the effect would give slightly low inflow rates.

Robinson and Rohwer (1959) studied seepage outflow. In highly permeable sand, seepage meters (one of which resembled the collector used in this study) gave higher values than seepage rings. They suggested this was due to breakage of a film of lower permeability when meters were installed. They also found that seepage outflow rates, as measured by seepage meters, decreased markedly with time (sometimes a reduction of more than 50% in the first week). I found no change in inflow with time and consistent flow rates were obtained immediately after setting the cylinder in the lake bed. This was probably because inflow and outflow are mechanically somewhat different, outflow being more affected by clogging by small particles that settle out of suspension and into the sediment.

Seepage Inflow

Southwestern Shore

Distribution

Seepage distribution along the southwestern shore of Lake Sallie (Figure 13) agrees generally with the results derived from the theoretical flow net (Figure 21) (drawn according to rules given by Cedergren, 1968) which assumes inflow from a homogeneous, isotropic surficial medium over an impermeable layer. A saturated thickness of 10 m is estimated from well-log data (McBride, Figures 4, 5, and 6; 1972a). The flow net shows that most of the flow occurs within 15 m of shore, yet field measurement indicated substantial flow extended to about 60 m from shore (Figure 13). This indicates that the media is anisotropic and that the horizontal dimension actually is 4 times greater than the vertical dimension. To make an anisotropic flow net orthogonal, the horizontal dimension of a section may be multiplied by the square root of the vertical to horizontal permeability ratio ($\sqrt{\frac{k_v}{k_h}}$) (Cedergren, 1968). Therefore, the horizontal to vertical permeability ratio is 16 (i.e., $4\sqrt{\frac{k_v}{k_h}} = 1$, so $\frac{k_h}{k_v} = 16$). This concurs with Weeks (1969) who reported horizontal to vertical permeability ratios of 2 to 20 from pump tests in glacial outwash in Wisconsin. Considerable information about permeability and sediment homogeneity might be obtained with seepage collectors and a small number of test holes.

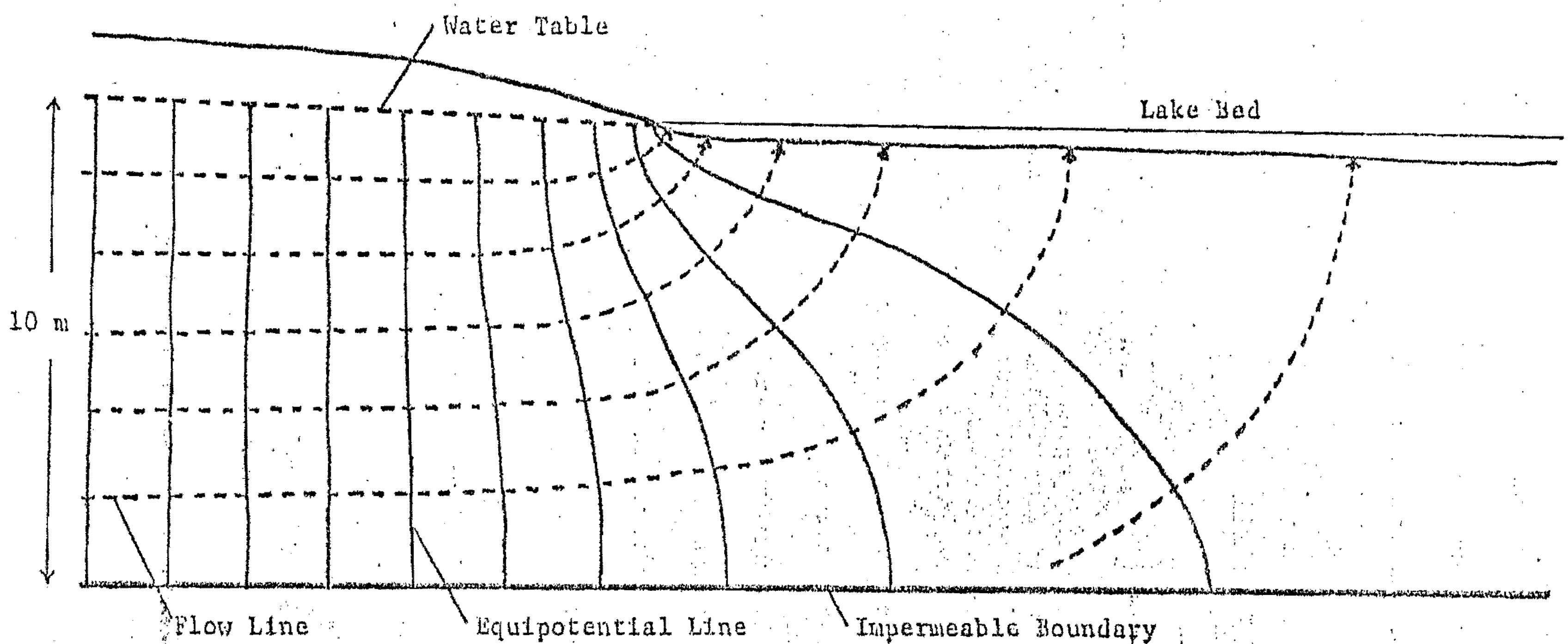


Fig. 21.--Theoretical flow net showing distribution of groundwater discharge into lake. Assumes inflow from a homogeneous, isotropic, surficial medium over an impermeable layer.

On a selected 800 m segment of the southwest shore of Lake Sallie, I found an annual inflow of 364 acre-ft/year. McBride (1972b) calculated 1968 acre-ft/year for the same segment. Considering the approximations involved, these figures agree rather closely. Permeability in outwash plains may range from 0.005 to 0.200 m/s (Terzaghi and Peck, 1967). McBride's data was taken from well logs spaced at approximately 0.6 km intervals. In this study, direct measurements were from points no greater than 0.24 km apart. The difference could not be accounted for on the basis of additional rainfall from June to December 1971, as there was no change in saturated thickness or in water-table gradient at measured wells (McBride, 1972b).

High-nitrate Zone

High nitrate values between Transects II and V (Figure 12) apparently came from two sources, septic tanks and cropland. Greatest concentrations occurred in seepage collected alongshore by the septic tanks, but substantial quantities were found down to the southern end of the cultivated land (Figure 12, Appendix). Most of this land has received 1.9 g nitrogen/m^2 per year in fertilizer and in 1968 was planted entirely in alfalfa (Bergquist, 1972), which may have left residual nitrogen (Stout and Burau, 1967). Per unit length, the nitrate discharged along the shoreline is equal to the nitrogen application on adjacent cropland, suggesting additional sources. The southeastward trend of groundwater moving from Fox Lake to Lake Sallie (McBride, Figure 9, 1972a) may account for the absence of high concentrations of nitrate in seepage at Transect I.

Nearly all the nitrate, but only 30% of the groundwater entered the lake within 6 m of shore at the study area. This, and the agreement of measured and theoretical seepage distribution indicates that a nitrate zone caps the water table. Deeper, more regional groundwater, discharged farther from shore, was low in nitrate. High concentrations of nitrate in shallow groundwater and low concentrations farther down are commonly reported (George and Hastings, 1951; Larson and Henley, 1966; Metzler, 1958; Stout and Burau, 1967; Nassau-Suffolk Research Task Group, 1969; and Polkowski and Boyle, 1970). This phenomenon appears to result from leaching of nitrate from the surface and lack of complete mixing in the saturated zone. In summary, the chemical and velocity data and the groundwater theory concur: near-lake contributions to groundwater are discharged near the shoreline.

Phosphorus

Phosphorus did not differ appreciably in inhabited and uninhabited areas. Applications of phosphorus have been shown by soil scientists (Stephenson and Chapman, 1931; Ellis and Erickson, 1969) to move very little in soil. The C horizon of a sandy soil adsorbed less phosphorus (0.55 mg P/100 g soil) than other soils tested by Ellis and Erickson, but recovered 91% of its initial adsorption capacity in 3 months. Although the presence of phosphorus in groundwater indicates that some moves through the soil, it could not be traced to septic tanks.

Northeastern Shore

Low concentrations of nitrate in seepage inflow on the northeast side of Lake Sallie may reflect the absence of nearby cropland or septic tanks. Comparison of inflow quality along this shoreline suggests that groundwater may carry nutrients from one lake to another. Inflow at

Collector 31E may come from local recharge or, as McBride's data suggest (Figures 4 and 5, 1972a), it may come from Lake Detroit by an outwash channel. Inflow at Collector 32C was two to three times richer in both phosphorus and nitrogen than 31E, implying that it may come from nearby, highly eutrophic, Muskrat Lake (see Figure 10).

Tracer Study at Station 14

An intensive septic-tank study on this shore indicated that a heavily-used septic tank contributes 40% of its nitrogen to the lake, most of it as nitrate, and that this input is superimposed on already high background levels. No phosphorus concentration above background was apparent beyond the first row of wells. Calculation of the nitrogen contribution was based on several approximations: 1) size of the area over which the input occurred, 2) nutrient output from the septic tank, and 3) background levels derived from average seepage concentrations in the uninhabited area 300 m downshore. Because nearshore seepage at this location contained the highest nitrogen concentrations found on the entire shore (Appendix), the conclusion that septic tanks contribute large quantities of nitrogen to the lake is inescapable.

The graph showing the concentration of ammonia, nitrite and nitrate nitrogen and distance from the septic tank (Figure 19) suggests that ammonia is nitrified to nitrate and that this is the dominant means by which nitrogen moves into the lake. However, loss of ammonia to the atmosphere either as free ammonia or as molecular nitrogen (N_2) from denitrification of nitrate (Frobisher, 1968) may be an important, alternate means of ammonia loss. The present evidence suggests that nitrification does in fact occur: 1) Ammonia concentration was high only in the clogged area (Wells 4 and 11) immediately opposite the discharge point. 2) Nitrate concentrations were higher near the discharge point than they were further away (higher at Wells 3, 5 and 6 than at 1 or 7). 3) Nitrate was usually highest along the major line of tracer flow (Wells 5 and 9, Table 13). The fact that Wells 4 and 11 and Collector 14E were consistently high in ammonia suggests that, after several years of continuous use, part of the effluent ammonia moves directly into the lake without nitrification.

Although wells were not screened at different depths, the seepage collectors served the same purpose (maybe better, because wells collect water above their screens) and indicated that mobile contaminants move just below the surface of the saturated zone and enter the lake near the shore.

Results are in general agreement with others. In laboratory study, Preul and Schroepfer (1964) found that nitrate is not retained by absorption in the usual pH ranges above 7.0. Preul (1967) said that a high percentage of the originally high concentration of ammonia (40 to 60 mg/liter) in septic tank effluents were highly nitrified less than 6 m after their release to the soil. Preul (1968) studied groundwater contaminants near ten waste stabilization ponds in sand and silt soils of Minnesota. He showed that concentrations of 4 to 20 mg/liter of phosphate in the ponds were reduced to 0.2 59 0.4 mg/liter in the groundwater within 3 m from the ponds. Absorption was considered the major factor in lowering the phosphate concentration within a short distance. However, out of 22 wells, two had average phosphate concentrations of nearly 3 mg/liter of phosphate at a distance of 30 m and 45 m from the stabilization pond. He attributed this to localized soil effect. In a study of septic-tank contributions to groundwater in Wisconsin, Polkowski and Boyle (1970) found groundwater concentrations of 0.162 to 0 mg/liter of total phosphate but concluded that chloride and nitrate were the only measured ions capable of moving through the soil.

Bracketing Septic Tanks

Results of the lakeward-landward sampling program agreed with the septic tank study at Station 14: nitrate nitrogen was, and phosphate was not, a highly mobile contaminant. Although lakeward-landward sampling was an attempt to study five sewage disposal sites simultaneously, it failed to provide direct evidence of nutrient movement into the lake. Shortcomings of this approach were overcome with seepage collectors and additional wells at one site.

Annual Additions of Nutrients to the Soil

Annually, septic tanks along the shore of Lake Sallie discharge 103 to 180 kg (226 to 396 lb) of phosphorus and 312 to 546 kg (687 to 1200 lb) of nitrogen to the subsurface soil. This estimate is based on 1) 0.19 m^3 of sewage per man-day (U.S. Department of Health, Education and Welfare, p. 44, 1967), 2) 20,000 to 35,000 man-days per year for Lake Sallie, 3) 27 g/m^3 of phosphorus and 82 g/m^3 of nitrogen in domestic septic-tank effluent (Nassau-Suffolk Research Task Group, 1969). Effluent concentrations in this report were not used in this calculation because they were based on only one septic tank. Because septic tank effluents are generally discharged over very limited areas (often with no tile drainage owing to the high permeability of some soils), and because they result in accumulations of phosphorus in the ground, it may be reasonable to consider them a potential hazard to the lake. The fact that I did not locate sources of phosphorus in groundwater entering the lake should not encourage further use of lakeside septic tanks. Rather it should encourage continued study.

SUMMARY

A simple, inexpensive, seepage collector permits direct measurement of groundwater inflow in the range 0.01 to 2.5 μm/s (0.003 to 0.71 ft/day). It can be used to obtain samples of groundwater inflow for chemical analysis and appears useful for groundwater studies.

Groundwater inflow contributed materially to lake volume. Inflow continued year-round at measurable rates but increased by a factor of two to three in spring. Along an 800 m shore, groundwater entered Lake Sallie at the rate of 4.50×10^5 m^3/year. The velocity of inflow was quite uniform along the margin of the lake but decreased exponentially with distance from shore, a pattern that is predictable on the basis of flow net construction and a small number of test holes.

About 300 kg of nitrate nitrogen entered Lake Sallie annually along 400 m of shore, and is apparently associated with, but not restricted to, fertilization of adjacent cropland.

Study of a lakeside septic tank, selected on the basis of heavy use and the presence of seepage inflow, indicated that 40% of its effluent nitrogen reached the lake. Contaminants traveled in a fan-shaped zone along the surface of the water table and entered the lake near the shoreline. Lakeside septic tanks appear to be an immediate source of nitrogen. Phosphate was fixed in the soil near the septic tank.

Comparison of seepage chemistry at two locations on the northeast shore suggested that nearby Muskrat Lake contributes not only groundwater but also phosphorus and nitrogen to Lake Sallie.

APPENDIX

CHEMICAL ANALYSIS AND MEASUREMENT OF SEEPAGE INFLOW

Date	Velocity, $\mu m/s$	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
Collector[1] 1A (23 m, 0.7 m)[2]						
1970						
19 September	0.222	2.40		1.38	0.021	0.043
	0.241	1.94		1.68	0.017	0.057
	0.356	2.12		1.78	0.025	0.034
	0.306	1.82		1.86	0.017	0.041
	0.247	1.86		1.78	0.019	0.038
	(lake)	(0.62)		(0.27)	(0.023)	(0.046)
Collector 1B (72 m, 0.8 m)						
1970						
*28 November	—	0.55		3.2	0.000	0.005
1971						
* 7 January	—	0.48		0.96	0.000	0.003
*17 April	—	0.49	0.74	1.15	0.000	0.004
	(lake)	(0.36)				
24 April	(lake)	(0.36)	(0.85)	(0.26)	(0.001)	(0.006)
* 8 June	0.102	0.55	1.00	1.54	0.000	0.005
8 June	(lake)	(0.36)	(0.82)	(0.24)	(0.000)	(0.005)
24 June	0.379					
	0.372					
6 July	0.341					
21 July	0.332	0.51	0.81	0.84	0.001	0.003
12 September	0.319	0.55	0.51	0.90	0.000	0.002
*24 September	0.261	0.28	0.44	1.02	0.000	0.002

[1]Refer to Fig. 12 for location.

[2]First figure in parentheses is distance from high water mark; second figure is depth.

*Indicates samples frozen for storage.

APPENDIX—Continued

		mg PO_4/liter		mg N/liter		
Date	Velocity μ m/s	Soluble Ortho-phosphate	Total Phosphate	Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
*15 October	0.242	1.62	0.66	0.93	0.000	0.003
*28 December	0.154	0.40	0.60	0.51	0.004	0.000
*30 December	0.204	0.12	0.18	0.79	0.000	0.003
Collector 1C (65 m, 0.8 m)						
1971						
7 January	0.024	0.30		2.68	0.006	0.022
17 April	0.068	0.20	0.74	0.78	0.000	0.005
	(lake)	(0.36)	(0.83)	(0.26)	(0.001)	(0.006)
8 June	0.059	0.27	1.00	1.06	0.000	0.005
Collector 1D (7 m, 0.41 m)						
1971						
29 August	1.392	1.35	2.70	1.65	0.000	0.001
Collector 1E (7 m, 0.55 m)						
1971						
17 June		0.97	2.60	0.61	0.002	0.009
18 June	0.755					
	0.747					
	0.767					
	0.742					
	0.732					
	avg 0.749					
24 June	0.904					
28 June	0.812	0.82	1.47	1.18	0.001	0.003
	0.829	0.92	1.33	1.17	0.001	0.004
	0.662					
	0.774					
	0.834					
	0.797					

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter Soluble Ortho-phosphate	Total Phosphate	mg N/liter Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
28 June (Cont.)	0.797					
	0.570	0.58	1.34	1.19	0.001	0.004
	0.808					
	avg 0.765	0.77	1.38	1.18	0.001	0.004
29 June	0.850	0.81	1.68	1.29	0.000	0.003
	0.817					
	0.902					
	0.822					
	avg 0.848					
30 June	0.845	0.63	0.85	1.54	0.000	0.006
	0.863					
	avg 0.854					
6 July	0.703					
9 July	0.752					
	0.766					
	0.717					
	avg 0.778					
10 July	0.740					
	0.662					
	avg 0.701					
11 July	0.745					
	0.729					
	avg 0.737					
19 July	0.802					
	0.806					
	0.693					
	avg 0.767					

APPENDIX--Continued

Date	Velocity μm/s	mg PO_4/liter Soluble Ortho-phosphate	Total Phosphate	mg N/liter Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
29 August	0.768	0.95	5.00	1.47	0.000	0.001
24 September	0.570	0.44	1.08	1.65	0.000	0.002
Collector 1F (7 m, 0.55 m)						
1971						
28 June[a]	0.668	0.56	1.81	0.18	0.000	0.003
	(lake)	(0.62)	(1.40)	(0.01)	(0.000)	(0.003)
	0.572					
	0.619					
	0.707					
	0.669					
	0.668					
	0.640					
	0.640					
	0.706	0.99	1.12	0.68	0.000	0.004
	avg 0.653					
29 June	0.712	1.25	1.51	1.35	0.001	0.004
	0.683					
	0.739					
	0.700					
	avg 0.709					
30 June	0.718	0.91	1.32	1.54	0.001	0.004
	0.737					
	avg 0.728					
6 July	0.618					
9 July	0.637					
	0.702					

[a]Sampling was started immediately after placement

APPENDIX--Continued

Date	Velocity, $\mu m/s$	mg PO_4/liter: Soluble Orthophosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
9 July (Cont.)	0.592					
	avg 0.644					
10 July	0.613					
	0.578					
	avg 0.596					
11 July	0.645					
	0.629					
	0.637					
	0.618					
	avg 0.632					
19 July	0.626					
	0.672					
	0.718					
	avg 0.672					
29 August	0.657	1.70	4.76	1.15	0.000	0.001
Collector 1G (7 m, 0.55 m)						
1971						
16 August	0.620	1.45	1.77	2.95	0.000	0.003
29 August	0.668	0.84	3.04	1.91	0.000	0.001
Collector 1H (6 m, 0.50 m)						
1971						
16 August	0.491	0.75	1.30	1.86	0.000	0.002
29 August	0.590	1.56	2.56	1.13	0.000	0.001

APPENDIX--Continued

		mg PO_4/liter		mg N/liter		
Date	Velocity, $\mu m/s$	Soluble Ortho-phosphate	Total Phosphate	Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
		Collector 2 (7 m, 0.8 m)				
1970						
28 November	0.000					
1971						
24 January	0.000					
7 February	0.0003					
6 March	0.0000					
4 April	0.0001					
16-21 April	0.0001					
26-31 May	0.0001					
3-8 June	0.0001	1.28	0.80	2.34		0.001
		Collector 3a (7 m, 0.49 m)				
1970						
17 October	0.213					
24 October	0.007	3.67		8.88	0.062	0.027
1 November	0.015	2.45		4.05	0.001	0.006
	(lake)	(0.02)		(0.26)	(0.002)	(0.007)
28 November	0.000					
1971						
24 January	0.007	0.55		1.90	0.042	0.018
2 February	0.0006					
4 April	0.061	0.90		2.97	0.005	0.025
16 April	0.0018	0.13	0.66	1.38	0.001	0.022
27 May	0.440					
	0.327					
	avg 0.384					
1 June	0.307	0.36		0.96	0.001	0.004
12 June	0.372	0.29	1.31	1.29	0.001	0.007
	0.328	0.17	0.21	1.14	0.005	0.006
	0.333					
	avg 0.346					

APPENDIX--Continued

Date	Velocity, μm/s	Soluble Ortho-phosphate (mg PO_4/liter)	Total Phosphate (mg PO_4/liter)	Ammonia Nitrogen (mg N/liter)	Nitrite Nitrogen (mg N/liter)	Nitrate Nitrogen (mg N/liter)
22 June	0.153					
23 June	0.260					
4 July	0.000					
6 July	0.043					
21 July	0.010					
23 July	0.0012					
12 September	0.0474					
24 September	0.097	0.69	0.76	2.30	0.008	0.012
30 December	0.000					
Collector 3B (57 m, 0.72 m)						
1970						
28 November	0.000					
1971						
24 January	0.006	1.10		2.94	0.005	0.009
7 February	0.000					
4 April	0.035					
26-31 May	0.000					
Collector 4 (14 m, 0.6 m)						
1970						
1 November		0.28		0.93	0.002	0.008
28 November	0.008					
1971						
6 March	0.054	0.92		2.0	0.002	0.002
4 April	0.140	0.44		5.8	0.002	0.010
	0.171					
	(lake)	(0.37)		(0.43)	(0.004)	(0.230)
1 June	0.724					
17 June	0.000[a]					
23 June	0.582					
24 June	0.597					

[a]Sediment plugged vent tube and was re-opened.

APPENDIX--Continued

Date	Velocity, $\mu m/s$	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
24 June	0.717					
4 July	0.626					
6 July	0.505					
Collector 5A (14 m, 1 m)						
1970						
9 September	0.920					
20 September	0.662					
	(lake)	(0.77)		(0.27)	(0.023)	(0.032)
27 September		0.78		1.67	0.001	0.005
28 November	0.011[a]					
1971						
* 7 January		0.49		0.27	0.004	0.030
*24 January	0.133	0.43		0.34	0.006	0.050
* 7 February	0.136	0.04		0.28	0.004	0.018
6 March	0.007[a]					
* 4 April	0.272	0.27		0.24	0.001	0.008
*	(lake)	(0.22)		(0.46)	(0.003)	(0.169)
*16 April	0.387	0.20	0.25	0.58	0.001	0.004
1 June	0.218	0.54		0.67	0.000	0.004
	(lake)	(0.06)		(0.18)	(0.001)	(0.000)
6 June	0.528					
7 June	0.468	0.50	0.63	0.53	0.000	0.004
	(lake)	(0.04)	(0.49)	(0.02)	(0.000)	(0.004)
8 June	0.354	0.20	0.22	0.56	0.000	0.004
	(lake)	(0.30)	(0.22)	(0.46)	(0.002)	(0.025)
12 June	0.300	0.18	0.19	0.08	0.001	0.004
	0.326					
	(lake)	(0.09)	(0.09)	(0.00)	(0.001)	(0.005)
17 June		0.66		0.43	0.000	0.004
	0.608					
22 June	1.220[b]					
	1.240					

[a]Poor connections in apparatus.

[b]First use of larger tube and bag.

APPENDIX--Continued

Date	Velocity, μm/s	mg PO_4/liter: Soluble Orthophosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
24 June	1.320					
	1.423					
4 July	1.523					
	1.521					
	1.572					
6 July	1.490					
20 July	1.288					
21 July	1.230	1.44	1.73	1.94	0.003	0.001
12 September	0.071[a]					
24 September	0.000a					
*15 October	0.701	0.10	0.68	1.81	0.001	0.011
*	(lake)	(0.10)	(0.24)	(0.07)	(0.001)	(0.006)
Collector 5 B (18 m, 0.080 m)						
1971						
6 June	0.318					
7 June	0.107	0.20	0.38	1.51	0.001	0.008
12 June	0.160	0.09		0.23		
17 June	0.196					
	0.309					
22 June	0.235					
	0.226					
23 June	0.260					
1 July	0.341	0.08	3.09	2.33	0.000	0.005
4 July	0.322	0.80	1.60	2.32	0.000	0.004
21 July	0.277	0.91	1.31	1.88	0.002	0.003
*15 October	0.250	0.10	0.56	1.28	0.000	0.002
Collector 5 C (14 m, 0.8 m)						
1971						
6 June	0.408					
7 June	0.340	0.21	0.46	1.31	0.001	0.008
	0.366					
12 June	0.273	0.16	0.43	0.29	0.007	0.004

[a]Sediment plugged the vent tube.

APPENDIX--Continued

		mg PO_4/liter		mg N/liter		
Date	Velocity, μ m/s	Soluble Ortho-phosphate	Total Phosphate	Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
Collector 5 D (10 m, 0.80 m)						
1971						
6 June	0.419					
7 June		0.74	2.5	3.44	0.003	0.020
12 June	0.366	0.29	1.31	1.29	0.001	0.007
22 June	0.286					
23 June	0.262					
1 July	0.318					
Collector 5 E (14 m, 0.80 m)						
1971						
6 June	0.310					
7 June	0.123	0.34	0.68	0.74	0.002	0.007
12 June	0.215	0.22	0.51	0.51	0.003	0.005
17 June	0.287					
22 June	0.294					
	0.276					
23 June	0.331					
	0.173					
1 July	0.385	0.40	2.46	3.0	0.000	0.005
4 July	0.408	0.63	2.00	2.8	0.000	0.004
	0.456					
21 July	0.337	0.56	0.16	0.34	0.003	0.001
*15 October	0.336	0.10	0.23	0.95	0.000	0.002
Collector 5 F (11.5 m, 0.75 m)						
1971						
6 June	0.026					
7 June	0.138	0.11	0.37	0.85	0.002	0.008
12 June	0.161	0.08	0.37	0.27	0.000	0.11
17 June	0.225					
22 June	0.272					
	0.272					
23 June	0.297					

APPENDIX--Continued

Date	Velocity, μm/s	mg PO_4/liter Soluble Ortho-phosphate	mg PO_4/liter Total Phosphate	mg N/liter Ammonia Nitrogen	mg N/liter Nitrite Nitrogen	mg N/liter Nitrate Nitrogen
Collector 5 G (25 m, 0.88 m)						
1971						
6 June	0.102					
7 June	0.026	0.23				
12 June	0.017	0.67				
17 June	0.102					
22 June	0.058					
	0.082					
23 June	0.095					
1 July	0.100	0.83	3.74	9.1	0.001	0.001
Collector 5 H (40 m, 0.91 m)						
1971						
7 June	0.013	0.24				
12 June	0.32	0.04	0.14	0.53	0.000	0.003
17 June	0.093					
22 June	0.051					
22 June	0.018					
23 June	0.075					
1 July	0.095	0.52	1.1	2.9	0.003	0.007
Collector 5 I (15 m, 0.74 m)						
1971						
12 June	0.010					
17 June	0.122					
22 June	0.114					
22 June	0.140					
23 June	0.025					
1 July	0.160					
Collector 5 J (55 m, 0.96 m)						
22 June	0.012					

APPENDIX—Continued

		mg PO_4/liter		mg N/liter		
Date	Velocity, μm/s	Soluble Ortho-phosphate	Total Phosphate	Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
22 June	0.008					
23 June	0.004					
Collector 5 K (3 m, 0.20 m)						
1971						
22 June	0.623					
	0.605					
	0.565					
23 June	0.817					
1 July	0.710	0.47	1.13	1.3	0.000	0.005
4 July	0.858					
	0.450					
	0.898					
6 July	0.920					
21 July	0.776	0.53	0.80	0.79	0.001	0.003
*15 October	0.732	0.91	0.50	0.70	0.000	0.003
12 November	0.743					
28 December	(lake)	(0.22)	(0.32)	(0.16)	(0.004)	(1.6)
30 December	0.805	0.14	0.40	0.36	0.000	0.005
30 December	(lake)	(0.07)	(0.14)	(0.13)	(0.002)	(0.11)
Collector 5 L (70 m, 1.2 m)						
1971						
22 June	0.008					
	0.006					
23 June	0.008					
Collector 5 M (15 m, 0.80 m)						
1971						
1 July	0.120					
4 July	0.175					
	0.209					

APPENDIX--Continued

Date	Velocity, μ m/s	Soluble Ortho-phosphate (mg PO_4/liter)	Total Phosphate (mg PO_4/liter)	Ammonia Nitrogen (mg N/liter)	Nitrite Nitrogen (mg N/liter)	Nitrate Nitrogen (mg N/liter)
Collector 5 N (15 m, 0.80 m)						
1971						
1 July	0.145					
4 July	0.139					
	0.212					
Collector 6 (30 m, 0.94 m)						
1970						
28 November	0.065	0.22		2.8	0.000	0.005
1971						
24 January	0.044	0.30		0.35	0.007	0.009
7 February	0.014	0.07		0.16	0.004	0.010
6 March	0.017	0.19		0.60	0.003	0.003
4 April	0.107	0.33		0.38	0.000	0.008
4 April	(lake)	(0.27)		(0.39)	(0.002)	(0.123)
8 May	0.081	0.73		0.28	0.000	0.010
8 May	(lake)	(0.08)		(0.03)	(0.000)	(0.003)
1 June	0.163	0.24		0.27	0.001	0.000
1 June	(lake)	(0.00)		(0.12)	(0.001)	(0.003)
17 June	0.282	0.43	0.71	0.39	0.001	0.005
17 June	0.337					
22 June	0.149					
24 June	0.254					
4 July	0.565	0.41	2.62	0.76	0.000	0.006
12 September	0.139	0.10		0.5	0.001	0.003
*24 September	0.105	0.01	0.20	1.08	0.000	0.012
Collector 7 (40 m, 0.9 m)						
1971						
24 January	0.012					
7 February	0.001					
16 April	(lake)	(0.27)	(0.80)	(0.42)	(0.001)	(0.001)
16-21 April	0.001	0.21	0.31	16.0	0.001	0.003

Date	Velocity, μ m/s	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
26-27 May	0.003					
27-31 May	0.001	0.40		0.51		0.16
8 June	(lake)	(0.27)	(0.80)	(0.40)	(0.001)	(0.001)
5-8 June	0.001	0.40	0.60	21.0	0.002	0.004
Collector 8 (15 m, 0.7 m)						
1970						
28 November	0.000					
1971						
24 January	0.019	0.35		14.4	0.20	0.34
7 February	0.002					
4 April	0.000					
16 April	0.000					
26-31 May	0.008	0.46		2.15	0.002	0.16
8 June	(lake)	(0.24)		(0.32)	(0.001)	(0.004)
Collector 9 (18 m, 0.75 m)						
1971						
6 March	0.000					
16 April	(lake)	(0.23)		(0.33)	(0.001)	(0.003)
16-21 April	0.000	0.11		1.14		0.007
4-8 June	0.002	0.65		0.26		0.003
Collector 8 (15 m, 0.7 m)						
1970						
28 November	0.000					
1971						
24 January	0.019	0.35		14.4	0.020	0.034
7 February	0.002					
4 April	0.000					
16 April	0.000					
26-31 May	0.008	0.46		2.15	0.002	0.016

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
8 June	(lake)	(0.24)		(0.32)	(0.001)	(0.004)
Collector 9 (18 m, 0.75 m)						
1971						
6 March	0.000					
16 April	(lake)	(0.23)		(0.33)	(0.001)	(0.003)
16-21 April	0.000	0.11		1.14		0.007
4-8 June	0.002	0.65		0.26		0.003
Collector 10 (4 m, 0.38 m)						
1971						
4 July	0.572					
	0.535					
6 July	0.623					
8 July	0.326	0.45	1.26	0.71	0.149	0.990
11 July		0.15	0.37	0.11	0.842	0.59
6 August	0.356					
17 August	0.384	0.82	0.50	0.33	0.224	2.27
20 August	0.265					
24 September	0.457	0.11	0.46	0.09	0.127	8.14
15 October	0.588	0.12	0.34	0.09	0.018	9.4
29 October	0.142	0.22	0.50	0.35	0.075	5.12
11 December	0.542	0.19	0.28	0.05	0.003	8.00
30 December	0.348	0.19	0.12	0.00	0.002	9.5
1972						
26 May	1.140	0.10	0.16	0.28	0.028	2.92
Collector 11 (9 m, 0.46 m)						
1971						
4 July	0.423					
	0.375					
	0.416					

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter Soluble Ortho-phosphate	mg PO_4/liter Total Phosphate	mg N/liter Ammonia Nitrogen	mg N/liter Nitrite Nitrogen	mg N/liter Nitrate Nitrogen
6 July	0.409					
8 July	0.365	0.32	0.62	0.56	0.075	0.025
11 July	0.465	0.36	0.29	0.28	0.333	0.475
26 July	0.265					
6 August	0.456					
19 August	0.276	0.45	0.19	0.22	0.016	0.484
*27 September	0.350	0.14	0.30	0.19	0.053	3.64
*15 October	0.425	0.11	0.64	0.05	0.017	4.40
Collector 12 (19 m, 0.75 m)						
1971						
4 July	0.216					
	0.254					
6 July	0.059					
8 July	0.143	0.92			0.007	0.001
11 July	0.198	1.14	1.87	4.9	0.000	0.004
26 July	0.116	0.96	1.35	1.94	0.000	0.004
26 July	0.284					
6 August	0.267					
*24 September	0.272	0.31	0.20	0.63	0.001	0.013
*15 October		0.21	0.74	0.48	0.000	0.003
*29 October	0.148	0.44	0.48	0.31	0.000	0.018
Collector 13 (13 m, 0.63 m)						
1971						
4 July	0.291					
	0.291					
6 July	0.210					
8 July	0.326	0.66	0.32	3.85	0.000	0.007
11 July	0.370	0.59	1.29	3.30	0.000	0.004
26 July	0.110	0.62	0.96	2.5	0.000	0.003
6 August	0.338					
*24 September	0.310	0.36	0.22	0.62	0.001	0.013
*15 October	0.288	0.22	0.54	0.42	0.000	0.003
*29 October	0.274	0.26	1.86	0.29	0.000	0.004

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
Station 14, Lake Concentrations						
1971						
11 September		0.44	0.82	0.00	0.000	0.003
17 September		0.30	0.72	0.04	0.001	0.015
24 September		0.22	0.58	0.08	0.000	0.002
* 1 October		0.28	0.56	0.04	0.000	0.003
26 October		0.20	0.40	0.02	0.001	0.026
6 November		0.08	0.50	0.01	0.002	0.053
27 November		0.07	0.14	0.03	0.001	0.004
*30 December near collector 14E		0.09	0.28	0.16	0.014	3.92
*30 December near collector 14N		0.14	0.31	0.03	0.001	0.340
Collector 14A (5 m, 0.2 m)						
1971						
23 October	0.154	0.25	0.34	0.57	0.191	3.55
	0.252	0.68	1.10	1.79	0.246	2.19
Collector 14B (7 m, 0.28 m)						
1971						
6 July	0.835					
8 July	0.803	0.53	0.97	0.18	0.294	3.87
11 July	0.369	0.21	0.56	0.16	0.747	2.34
21 July	0.683	0.49	0.49	0.35	0.219	3.76
26 July	0.522	0.20	0.71	0.49	0.219	3.84
6 August	0.615					
17 August	0.636	0.50	0.55	0.64	0.349	3.04
24 August	0.583	0.68				
29 August	0.585	0.64				
12 September	0.685	0.44	0.38	0.90	0.163	7.3
17 September	0.723	0.64	0.97	0.16	0.106	9.6
*24 September	0.615	0.64	0.48	0.22	0.128	8.97
24 September	0.600					

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
* 1 October	0.600	0.96		0.17	0.16	8.54
26 October	0.623	0.15	0.54	0.13	0.102	10.0
6 October	0.612	1.85	0.78	0.01	0.024	10.8
27 October	0.276	0.16	0.20	0.08	0.017	12.3
*30 December	0.543	0.14	0.32	0.00	0.000	8.8
Collector 14C (7 m, 0.3 m)						
1971						
11 September	0.635	0.50	0.48	1.06	0.636	2.2
17 September	0.589	0.44	0.74	0.70	0.746	5.8
24 September	0.605	0.31	0.28	0.53	0.913	4.7
23 October	0.522	0.22	0.90	0.39	0.046	4.76
6 November	0.190	1.78	0.44	0.32	0.572	5.33
Collector 14D (7 m, 0.3 m)						
1971						
11 September	0.722	1.21	1.06	1.3	0.065	0.91
17 September	0.744	0.50	1.20	0.79	0.086	1.97
24 September	0.158	0.44	0.56	0.50	0.105	1.51
* 1 October	0.710	0.46	0.44	0.35	0.149	3.52
23 October	0.710	0.46	0.44	0.35	0.149	3.52
6 November	0.763		0.28	0.15	0.033	5.32
27 November	0.715	0.18	0.22	0.05	0.020	5.62
Collector 14E (7 m, 0.28 m)						
1971						
19 August	0.640	0.27	0.89	5.7	0.001	0.005
24 August	0.682	0.52				
*29 August	0.328	0.63				
11 September	0.743	0.71	0.65	2.93	0.083	8.9
17 September	0.790	0.75	1.55	2.28	0.046	10.0
24 September	0.507	0.44	0.54	2.95	0.041	10.0
23 October	0.710	0.29	0.52	2.95	0.102	20.3

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter Soluble Ortho-phosphate	Total Phosphate	mg N/liter Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
6 November	0.777	1.14	0.80	2.35	0.039	16.0
27 November	0.764	0.17	0.22	2.09	0.052	13.2
30 December	0.487	0.08	0.32	3.4	0.037	14.
1972						
26 May	1.030	0.30	0.30	2.48	0.072	16.0
Collector 14F (5 m, 0.2 m)						
1971						
23 October	0.233	0.29	0.44	0.57	0.390	12.5
6 November	0.690	0.60	0.70	0.60	0.213	17.6
Collector 14G (7 m, 0.3 m)						
1971						
* 1 October	0.640	0.34	0.64	1.10	0.007	0.017
23 October	0.248	0.33	1.16	1.67	0.002	0.004
6 November	0.356	0.64	0.60	0.50	0.058	2.24
Collector 14H (7 m, 0.3 m)						
1971						
* 1 October	0.281	1.16	1.12	2.34	0.005	0.019
23 October	0.108	1.93	2.82	5.7	0.003	0.018
6 October	0.043	2.2	2.06	4.9	0.006	0.031
Collector 14I (7 m, 0.3 m)						
1971						
* 1 October	0.317	0.33	1.04	2.19	0.002	0.013
23 October	0.304	0.92	5.08	5.5	0.001	0.008
6 November	0.358	0.56	0.56	1.08	0.143	2.43

APPENDIX--Continued

Date	Velocity, m/s	Soluble Ortho-phosphate (mg PO_4/liter)	Total Phosphate (mg PO_4/liter)	Ammonia Nitrogen (mg N/liter)	Nitrite Nitrogen (mg N/liter)	Nitrate Nitrogen (mg N/liter)
Collector 14J (7 m, 0.28 m)						
1971						
19 August	0.352	0.38	0.80	1.18	0.045	
24 August	0.562	0.55				
29 August	0.476	0.79				
11 September	0.457	1.26	1.36	1.40	0.023	0.400
17 September	0.588	0.64	0.97	0.46	0.001	9.46
24 September	0.448	0.62	0.80	0.56	0.111	8.29
* 1 October	0.470	0.22		0.32	0.17	8.27
23 October	0.522	0.47	1.08	0.31	3.74	50.4
6 November	0.584	0.86	0.40	0.28	0.048	11.7
Collector 14K (12 m, 0.44 m)						
1971						
11 September	0.713	1.08	0.62	0.83	0.004	
17 September	0.760	1.00	1.12	0.60	0.001	0.081
24 September	0.756	0.48	0.58	0.54	0.000	0.004
1 October	0.602	0.21		0.44	0.000	0.003
23 October	0.789	0.10	0.36	0.25	0.000	0.003
6 November	0.835	1.04	3.26	0.20	0.001	0.003
27 November	0.492	0.11	0.20	0.17	0.002	0.003
*30 December	0.743	0.21	0.32	0.20	0.000	0.003
Collector 14L (12 m, 0.70 m)						
1971						
11 September	0.955	0.52	0.46	0.54	0.000	0.002
17 September	0.680	1.12	0.90	0.65	0.000	0.007
24 September	0.805	0.58	0.62	0.58	0.000	0.002
1 October	0.781	0.25	0.40	0.35	0.000	0.002
23 October	0.720	0.29	0.44	0.24	0.001	0.003
6 November	0.748	1.42	0.36	0.18	0.001	0.003
Collector 14M (12 m, 0.44 m)						
1971						
11 September	0.370	0.81	0.85	1.68	0.012	0.187
17 September	0.370	0.72	1.18	1.18	0.000	0.022
24 September	0.322	0.62	0.54	1.05	0.000	0.004
1 October	0.607	0.21	0.50	0.81	0.000	0.009
23 October	0.390	0.27	0.36	0.37	0.000	0.005

APPENDIX—Continued

Date	Velocity, μ m/s	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
6 November	0.037[a]					
27 November	0.000[a]					
Collector 14N (17 m, 0.52 m)						
1971						
11 September	0.790	0.70	0.67	0.90	0.001	0.002
17 September	0.786	1.15	1.52	0.65	0.000	0.006
24 September	0.538	0.86	0.56	0.53	0.000	0.002
* 1 October	0.808	0.24	0.50	0.43	0.000	0.002
23 October	0.862	0.09	1.14	0.24	0.001	0.004
6 November	0.685	1.34	0.44	0.12	0.001	0.003
27 November	0.747	0.17	0.28	0.11	0.001	0.002
*30 December	0.650	0.02	0.28	0.16	0.000	0.004
Collector 14P (50 m, 0.9 m)						
1971						
11 September	0.224	0.96	1.50	3.57	0.001	0.004
17 September	0.200	1.44	1.17	12.0	0.002	0.014
24 September	0.013					
* 1 October	0.249	0.35	1.34	2.95	0.000	0.003
30 December	0.260					
Collector 15 (5 m, 0.3 m)						
1971						
6 July	0.473					
8 July	0.565	1.26	3.5	1.88	0.000	0.009
11 July	0.614	0.16	3.52	1.1	0.000	0.002
26 July	0.115	1.67	3.52	4.5	0.000	0.007
6 August	0.257					
17 August	0.297	1.46	1.24	3.7	0.000	0.000

[a]Low values were due to gas accumulations in the cylinder.

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
*24 September	0.507	0.24	0.36	1.05	0.000	0.002
*15 October	0.420	0.24	0.40	0.90	0.000	0.002
*29 October	0.508	0.15	0.34	0.54	0.000	0.001
*11 December		0.16	0.24	0.28	0.000	0.002
*11 December	(lake)	(0.02)	(0.48)	(0.12)	(0.000)	(0.004)
Collector 16 (90 m, 1.15 m)						
1971						
19 July	0.013					
20 July	0.073					
23 July	0.016					
Collector 17 (100 m, 1.5 m)						
1971						
19 July	0.073					
20 July	0.062					
21 July	0.006					
Collector 17 (100 m, 1.5 m)						
1971						
19 July	0.073					
20 July	0.062					
21 July	0.006					
Collector 18 (80 m, 1.2 m)						
1971						
19 July	0.063					
21 July	0.008					
24 July	0.075					
6 August	0.034					

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
Collector 19 (110 m, 1.5 m)						
1971						
19 July	0.032					
21 July	0.002					
23 July	0.003					
Collector 20 (90 m, 1.6 m)						
1971						
24 July	0.115					
6 August	0.286					
Collector 21 (160 m, 1.5 m)						
1971						
21 July	0.004					
Collector 22 (25 m, 0.9 m)						
1971						
23 July	0.156					
28 July	0.092	0.85	1.77	5.8	0.000	0.001
6 August	0.155					
*24 September	0.394	0.27	0.48	0.89	0.000	0.003
Collector 23 (60 m, 0.9 m)						
1971						
23 July	0.008					
24 July	0.007					

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrite Nitrogen	mg N/liter: Nitrate Nitrogen
Collector 24 (55 m, 1.0 m)						
1971						
24 July	0.029					
Collector 25 (7 m, 0.28 m)						
1971						
19 August	0.146	0.29	0.22	0.93	0.118	
*24 September	0.254	0.25	0.80	0.66	0.145	6.37
*15 October	0.402	0.60	0.44	0.43	0.128	6.15
Collector 26 (9 m, 0.50 m)						
1971						
19 August	0.605	0.20	0.29	1.06	0.004	
*24 September	0.457	0.23	0.20	0.64	0.138	3.78
*15 October	0.236	0.70	0.56	4.8	0.027	0.30
*11 December	0.432	0.10	0.20	0.20	0.036	3.52
*30 December	0.484	0.12	0.32	0.28	0.038	3.40
Collector 27 (11 m, 0.5 m)						
1971						
19 August	0.286	0.20	0.15	0.62	0.001	
*24 September	0.406	0.24	0.40	0.96	0.000	0.003
Collector 28 (9 m, 0.5 m)						
1971						
19 August	0.392	0.40	0.38	0.87	0.000	0.003
*24 September	0.437	0.15	0.24	0.35	0.039	5.73

APPENDIX--Continued

Date	Velocity, μm/s	mg PO_4/liter: Soluble Ortho-phosphate	mg PO_4/liter: Total Phosphate	mg N/liter: Ammonia Nitrogen	mg N/liter: Nitrate Nitrogen	mg N/liter: Nitrate Nitrogen
		Collector 29 (5 m, 0.2 m)				
1971						
*29 October	0.660	0.08	0.62	0.34	0.146	4.14
		Collector 30 (5 m, 0.2 m)				
1971						
*29 October	0.780	0.19	0.44	0.34	0.187	2.44
28 December	(lake)	(0.31)	(0.44)	(0.14)	(0.054)	(4.90)
		Collector 31A (10 m, 0.5 m)				
1971						
20 July	0.646					
		Collector 31B (10 m, 0.5 m)				
1971						
24 July	1.110					
		Collector 31C (10 m, 0.5 m)				
1971						
24 July	0.297					
		Collector 31D (10 m, 0.5 m)				
1971						
24 July	0.336					

APPENDIX--Continued

Date	Velocity, μ m/s	mg PO_4/liter Soluble Ortho-phosphate	Total Phosphate	mg N/liter Ammonia Nitrogen	Nitrite Nitrogen	Nitrate Nitrogen
Collector 31E (9 m, 0.55 m)						
1971						
24 July	1.02					
26 July	1.14					
	1.05					
28 July	1.07	0.45		0.80	0.000	0.001
6 August	0.946					
18 August	0.903	0.62				
*24 September	1.05	0.17	0.40	0.74	0.000	0.002
*16 October	1.06	0.36	0.40	0.83	0.000	0.003
*29 October	1.32	0.16	0.78	1.02	0.000	0.002
Collector 32A (9 m, 0.5 m)						
1971						
18 August	2.15	1.40				
Collector 32B (9 m, 0.5 m)						
1971						
18 August	0.732	1.35				
Collector 32C (9 m, 0.5 m)						
1971						
18 August	2.58	1.50				
12 September	0.818	1.94	2.33	0.30	0.000	0.002
17 September	2.38					
17 September	2.34	1.13	0.83	3.57	0.000	0.002
*24 September	2.42	1.30	1.92	3.71	0.000	0.001
*16 October	1.99	1.02	1.80	4.0	0.000	0.002
*29 October	1.82	1.14	1.88	3.85	0.000	0.002

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